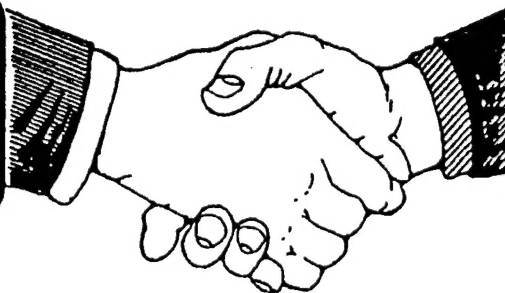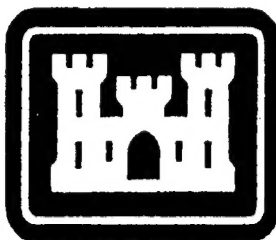# CONSTRUCTION PRODUCTIVITY ADVANCEMENT RESEARCH (CPAR) PROGRAM

## An Improved Building Energy Performance Commissioning Process Based on Short-Term Testing

by

Janette Manke, Douglas C. Hittle, Dahtzen Chu, and Ed Hancock

DTIC QUALITY INSPECTED 3

**A Corps/Industry Partnership To Advance Construction Productivity and Reduce Costs**

## USER EVALUATION OF REPORT

REFERENCE: USACERL Technical Report 96/78, *An Improved Building Energy Performance Commissioning Process Based on Short-Term Testing*

Please take a few minutes to answer the questions below, tear out this sheet, and return it to USACERL. As user of this report, your customer comments will provide USACERL with information essential for improving future reports.

1. Does this report satisfy a need? (Comment on purpose, related project, or other area of interest for which report will be used.)

_____

_____

_____

2. How, specifically, is the report being used? (Information source, design data or procedure, management procedure, source of ideas, etc.)

_____

_____

3. Has the information in this report led to any quantitative savings as far as manhours/contract dollars saved, operating costs avoided, efficiencies achieved, etc.? If so, please elaborate.

_____

_____

4. What is your evaluation of this report in the following areas?

a. Presentation: _____

b. Completeness: _____

c. Easy to Understand: _____

d. Easy to Implement: _____

e. Adequate Reference Material: _____

f. Relates to Area of Interest: _____

g. Did the report meet your expectations? _____

h. Does the report raise unanswered questions? _____

i. General Comments. (Indicate what you think should be changed to make this report and future reports of this type more responsive to your needs, more usable, improve readability, etc.)

_____

_____

_____

_____

_____

_____

5. If you would like to be contacted by the personnel who prepared this report to raise specific questions or discuss the topic, please fill in the following information.

Name: _____

Telephone Number: _____

Organization Address: _____

_____

_____

6. Please mail the completed form to:

Department of the Army
CONSTRUCTION ENGINEERING RESEARCH LABORATORIES
ATTN: CECER-TR-I
P.O. Box 9005
Champaign, IL 61826-9005

# REPORT DOCUMENTATION PAGE

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

| 1. AGENCY USE ONLY (Leave Blank) | 2. REPORT DATE | 3. REPORT TYPE AND DATES COVERED |
|---|---|---|
| | July 1996 | Final |

**4. TITLE AND SUBTITLE**

An Improved Building Energy Performance Commissioning Process Based on Short-Term Testing

**5. FUNDING NUMBERS**

FAD
90-080398, dated 27 Jun 90

**6. AUTHOR(S)**

Janette Manke, Douglas C. Hittle, Dahtzen Chu, and Ed Hancock

**7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)**

U.S. Army Construction Engineering Research Laboratories (USACERL)
P.O. Box 9005
Champaign, IL 61826-9005

**8. PERFORMING ORGANIZATION REPORT NUMBER**

TR 96/78

**9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)**

Headquarters, U.S. Army Corps of Engineers
ATTN: CEMP-CE
20 Massachusetts Ave. NW
Washington, DC 20314-1000

**10. SPONSORING / MONITORING AGENCY REPORT NUMBER**

**11. SUPPLEMENTARY NOTES**

Copies are available from the National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161.

**12a. DISTRIBUTION / AVAILABILITY STATEMENT**

Approved for public release; distribution is unlimited.

**12b. DISTRIBUTION CODE**

**13. ABSTRACT (Maximum 200 words)**

As buildings become more complex or take on new functions, new operational problems tend to surface. These include excessive energy costs, malfunctioning mechanical equipment, and uncomfortable working conditions. Energy-related problems often can be identified and documented for correction through the process called commissioning. Commissioning could have a major positive impact on institutional energy bills and occupant comfort, but the procedures currently available are not standardized and are variously flawed. Problems include limited scope and quality control of inputs to building design model, need for inconveniently long-term energy flow data, and failure to provide substantial diagnostic information to correct problems.

As part of the Army Corps of Engineers Construction Productivity Advancement Research (CPAR) Program, the U.S. Army Construction Engineering Research Laboratories (USACERL) and Colorado State University developed and demonstrated an inexpensive commissioning procedure based on short-term energy monitoring and performance testing. This commissioning procedure was field-tested on commercial-scale buildings of various design and locale. The procedure successfully revealed defects in the design, contruction, or operations of each building tested.

**14. SUBJECT TERMS**

Construction Productivity Advancement Research Program (CPAR)
energy efficient
building energy performance commissioning

**15. NUMBER OF PAGES**

164

**16. PRICE CODE**

| 17. SECURITY CLASSIFICATION OF REPORT | 18. SECURITY CLASSIFICATION OF THIS PAGE | 19. SECURITY CLASSIFICATION OF ABSTRACT | 20. LIMITATION OF ABSTRACT |
|---|---|---|---|
| Unclassified | Unclassified | Unclassified | SAR |

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std 239-18
298-102

# Foreword

# Contents

# List of Tables and Figures

# 1 Introduction

## 1.1 Background

As buildings become more complex or take on new functions, new operational problems tend to surface. These can include unexpectedly high energy costs, malfunctioning heating, ventilating, and air conditioning (HVAC) equipment, and uncomfortable working conditions. It is commonly understood that improperly functioning energy systems overconsume energy by an average of one-third. This poor performance can be caused by inadequate construction quality, incorrect design, or a combination of the two. Energy-related problems often can be identified and documented for correction through the process called *commissioning*.

Commissioning is an evolving testing and analysis methodology intended to help ensure that a building will function as effectively as was intended by the designers. The concept of commissioning was developed during the 1980s, but today it is practiced only to a limited extent in the management of Army buildings. It is difficult for the Army to exploit the benefits of the commissioning process due to the lack both of Army-specific and industry-standard guidance.

Conventional construction quality-checking methodologies generally do not consider the energy performance of building materials. There are no quality controls on the accuracy of inputs to the design model, and many measurement-based commissioning procedures for HVAC components are incomplete and inaccurate. Other problems with current energy performance assessment measures include:

- the need for a year's worth of energy-flow data
- failure to seriously consider changes in internal heat gains from lights, space heaters, etc.
- vulnerability to considerable error for any given building
- failure to provide substantial diagnostic information.

A practical, usable energy performance commissioning procedure would require

- short-term energy monitoring for ease of data collection and the least possible disruption of facility operations

- reliable energy-flow sampling methods
- modeling methods and technologies that could accurately represent the dynamics of all significant energy flows in any given building
- reporting functions that could identify and explain differences between a building's measured performance and its design specifications.

In everyday terms, the commissioning procedure would answer the following questions:

1. Will the building's design energy performance target be achieved?
2. Does energy subsystem performance deviate from design specifications—and if so, why?
3. What adjustments should be made on poorly performing subsystems?

Both the Army and the U.S. construction industry could benefit substantially from an accurate building energy performance commissioning process that addresses the shortcomings of existing processes while avoiding their heavy data requirements. The Construction Productivity Advancement Research (CPAR) Program was created to improve the productivity and competitiveness of the U.S. construction industry through cooperative research and development, field demonstration, transfer, and commercialization of innovative construction technologies. The U.S. Army Construction Engineering Research Laboratories (USACERL) was tasked to coordinate a CPAR Cooperative Research and Development Agreement (CRDA) to investigate methodologies and technologies that could improve the effectiveness of building energy commissioning procedures for the Army and private-sector users.

## 1.2  Objective

The objective of this work was to develop and demonstrate an effective building energy performance commissioning procedure based on practical short-term energy-systems performance testing.

## 1.3  Approach

The commissioning procedure requires two components: (1) hardware for data measurement and recording and (2) software for analyzing the data.

For the hardware component, the research team used the Short-Term Energy Monitoring (STEM) procedure, developed by the National Renewable Energy

Laboratory (NREL), to draft testing protocols for an entire building and its major energy subsystems. Instrumentation required for the testing was identified and acquired. The protocols were implemented on a test building and data were collected. Next, the researchers used the USACERL-developed Building Loads and System Thermodynamics (BLAST) software package for building modeling and energy-flow analysis. To address discrepancies between design energy performance and the actual test data, the researchers developed a model-calibration procedure. The completed commissioning procedure was then field-tested on buildings of various design and locale.

## 1.4 Public Domain Tools Used in This Study

BLAST (see section 1.3 above) software and documentation is available through the BLAST Support Office, University of Illinois at Urbana-Champaign. Call 217-333-3977 for information, or send Internet e-mail to Support@IBLAST.ME.UIUC.EDU.

The BLAST file editor (BLASTED) referred to in this report may be available through Colorado State University, Fort Collins, CO. For information on the availability of BLASTED, contact Douglas C. Hittle at CSU; call 970-491-8617, or send Internet e-mail to Hittle@LONGS.LANCE.COLOSTATE.EDU.

## 1.5 Units of Weight and Measure

U.S. standard units of measure are used throughout this report. A table of metric conversion factors is presented below.

**Metric conversion factors**

| | | |
|---|---|---|
| 1 in. | = | 25.4 mm |
| 1 ft | = | 0.305 m |
| 1 sq ft | = | 0.093 m$^2$ |
| 1 sq ft/min | = | 0.093 m$^2$/min |
| 1 cu ft | = | 0.028 m$^3$ |
| 1 mi | = | 1.61 km |
| 1 lb | = | 0.453 kg |
| 1 gal | = | 3.78 L |
| 1 psi | = | 6.89 kPa |
| 1 μm | = | 1x10$^{-6}$m |
| °F | = | (°C × 1.8) +32 |

# 2 Overview of the Building Energy Performance Commissioning Procedure

## 2.1 Problems with Commissioning Procedures

Typically, the energy performance of a building has been determined on the basis of utility bill information. This may provide a general idea of how the building performs, but is more indicative of the behavior of different occupants than of actual building characteristics. Another concern is the time required before an analysis can be completed, which is typically one year, the time of occupancy before a complete data set becomes available. For a new building, this procedure is obviously not possible.

A different approach is to estimate building energy performance based on mathematical models using the building plans and an hourly simulation analysis. The weather data for such simulations are based on measurements collected over several years and a standard building occupancy schedule is assumed. Analysis using this method allows a large degree of uncertainty with respect to the accuracy of the building model. Buildings are very complex, and accurate descriptions of material properties and actual construction details are difficult to verify. Because the building construction plays a major role in the building energy performance, the final estimate is subject to significant error. Additional error can be attributed to the difficulty in describing an adequate mathematical model. With these uncertainties, energy measurements for each specific building are necessary for a more accurate evaluation of the building energy performance.

## 2.2 Short-Term Energy Monitoring

To remedy these deficiencies, the National Renewable Energy Laboratory (NREL) developed a method that uses both measured building results and theory to simulate the performance of a building model. The Short-Term Energy Monitoring (STEM) project combines a short-term energy test with the Primary and Secondary Terms Analysis and Renormalization (PSTAR) renormalization process to develop a building model that best simulates the actual building energy performance. The STEM

protocol calls for a short-term (typically 3 days) test of an unoccupied building to evaluate the building envelope and mechanical systems. The test provides the data used to renormalize building coefficients used to predict the major energy flows in a building. With the renormalized model, the long-term expected energy use of the building can be predicted.

PSTAR renormalizes a building simulation model using the data from a short-term energy test performed on the unoccupied building. Because the simulation model parameters will be adjusted, the model can be a fairly simple interpretation of the building plans. In the analysis, adjustment factors are identified for each of three key building heat flows:

1.    heat flow per degree of inside-outside temperature difference under steady-state conditions (the building loss coefficient, or BLC)
2.    heat stored in the building internal mass
3.    heat from solar gains.

The renormalization process involves adjusting the previously identified factors until the heat flows from the building model best fit those from the measured data. The renormalized model is then used to determine HVAC performance by using the building as a dynamic calorimeter, and to estimate long-term performance using typical weather data and occupancy patterns. The renormalization process can reveal deficiencies in the building envelope or in the heating and air conditioning system performance.

## 2.3  Applicability of the BLAST Program

This project developed a similar approach using the Building Loads Analysis and System Thermodynamics (BLAST) program to simulate building energy performance. The BLAST program allows hour-by-hour detailed energy analysis of a building. Based on the building plans and physical observations of the structure, a base building model was developed for input to BLAST. A selection of physical building parameters, such as the insulation R-value or internal mass thickness, were systematically varied for each simulation run. By incrementally changing the building parameters to minimize the root-mean-square (rms) error between the measured building energy demand and the energy demand generated by the BLAST simulation, a calibrated building model was developed that performs most like the actual building during the test period.

BLAST was developed USACERL and has been used widely by the Corps of Engineers for designing energy-efficient buildings. Ideally, the program is used at the design phase to evaluate architectural tradeoffs based on energy and first costs. The objective was to extend the application of the BLAST program to include performance diagnostics. This included developing an automated calibration technique that adjusts BLAST parameters to minimize the rms error between the measured building performance and the predicted performance. For example, if BLAST predicts higher-than-measured heating loads in the building model, the value for the wall insulation parameter might need to be decreased.

Developing an automated tuning protocol to use with the BLAST program allowed discrepancies between expected and measured performance to be more clearly identified, and the reasons for these discrepancies to be pinpointed. For example, if the heating loads were as predicted but the gas consumption for a building was thirty percent too high, a problem can be expected with the performance of the boiler or furnace. The predictions of the calibrated model can also be compared with those of the design model to determine if the energy targets for the building can be achieved.

## 2.4  Commissioning Procedure Sequence

The commissioning procedure developed in this work was field-tested and fine-tuned on four buildings during the latter part of the project (one of which was tested but not modeled for reasons explained in section 1.3). The following general approach was used for all the buildings:

- develop a STEM test protocol
- install sensors and data loggers onsite, and collect quantitative data
- create base building model data set for use in BLAST
- determine the building parameters that significantly contribute to and can change the energy performance of the building
- vary building parameters to achieve a best fit between measured data and BLAST results
- simulate the building with existing building air-handling system and central plant to calculate total building energy performance.

It should be noted that the Director Building in Portland, OR—one of the facilities tested in this project—was not actually modeled and subjected to the entire commissioning process as part of this project. It was understood that this 8-story structure would be too large and complex to model using the same approach applied to the

other three buildings. However, one of the utility groups participating in this project requested that the Director Building be used to study the feasibility of applying a STEM-based testing protocol to large-scale buildings.

The remainder of this report describes in detail the development and field application of the commissioning procedure. The appendices provide detailed material pertaining to the model calibration procedure and related technical issues as follows:

- Appendix A documents how the building models were calibrated in this research, and discusses general conclusions about the model calibration procedure
- Appendix B reproduces the BLAST input deck for the Bell Avenue School
- Appendix C is a general user's manual for the BLAST Editor (BLASTED)
- Appendix D is a BLASTED manual for advanced users
- Appendix E reproduces the input deck for TRNSYS, a program used to prepare solar radiation input data for inclusion in the BLAST input deck
- Appendix F reproduces the PERL scripts used to automate the model calibration procedure
- Appendix G describes in detail the four buildings studied in this project.

An original subobjective of this research was to develop commissioning procedures that could be applied by minimally skilled technicians with little additional training. However, it soon became clear that dramatic process simplification was not feasible concurrently with research and development, so this subobjective was deferred to future stages of process development.

It should be noted that NREL has continued working on its own STEM-based approach to simulating building energy performance. That effort, the product of which will be a Windows[*]-based STEM program, is focusing more closely on software usability issues. The results of this concurrent NREL work will be evaluated for possible inclusion in future USACERL research.

---

[*] Windows is a registered trademark of Microsoft Corp., Redmond, WA.

# 3  Short-Term Test Protocol

This chapter describes the STEM test protocol—primarily work that was performed in the field—and discusses preparation and preliminary logistics, description of the instruments and measurements to be made, installation of the equipment at the site, data collection, and data processing. Case studies are included as examples of applications of the field protocol. The text discusses the general STEM test protocol developed and used during the program, and is intended as a guideline for future tests.

## 3.1  Typical Test Sequence

The typical STEM test sequence lasts 3 to 5 days and involves controlling the zone temperatures to a prescribed protocol while measuring the major energy flows in the building. Instruments are temporarily installed at the test site to measure the major energy flows in the building. The test protocol usually consists of a period during which temperatures are controlled to be constant (over time) and uniform (over space), and another period during which temperatures are allowed to change. The "constant and uniform" period is referred to as *coheating*, and the "changing" period is referred to as *cooldown*. The coheating period is specifically intended to provide data for a good estimate of the building load coefficient (BLC) during nighttime periods when heat flows other than conduction through the shell are smallest. The cooldown period is scheduled for a nighttime period and is intended to provide data for a good estimate of the effective thermal capacitance of the building. The effective thermal gain parameter is estimated from data during the daytime. The set points for heating during the daytime remain constant, but the zone temperatures may rise in response to solar gains.

It was usually specified that the building be unoccupied during all or part of the protocol. This was done both to minimize the effect the occupants have on the energy use in the building and to minimize any inconvenience to the occupants due to changing temperatures or installation of temporary instrumentation. Weekends and holidays are frequently a good choice for scheduling STEM tests. Buildings which are newly completed but not occupied may be good candidates for testing also.

Electric heaters were installed to implement this control in smaller buildings (less than 10,000 sq ft), and the existing heating and cooling system were used where installing large numbers of heaters was impractical. The objective is to maintain constant and uniform temperatures during the coheating period. The major components of the energy balance are well known, which means that heat flows must be either small or carefully measured. Electric heaters are used to provide energy at a rate which is easy to control and measure. Simply measuring the fuel input to a gas furnace is not adequate because the actual heat flow to the conditioned space of the building cannot be accurately determined without knowing the furnace combustion and delivery efficiency. If electric heaters are not or cannot be used, then the heat flow required to maintain the temperature with the existing heating and cooling system must be measured directly. This usually means measuring a flow rate and temperature difference for either an air or liquid flow, such as at a heating or cooling coil.

Testing may be a mild inconvenience to the occupants. Maintaining good tenant rapport and encouraging occupant cooperation and participation is recommended.

## 3.2 Preliminary Preparations

A significant effort is involved in preparing for a short-term test. Because the test itself is of limited duration, all of the activities during the test must be carefully planned in advance. First, consider the specific question that you want to try to answer during the test. For example, questions may focus on the shell of the building, its HVAC system and controls, or other specific features. The thermal parameters of the building shell were usually estimated as a first step in the test. Several details of the building and its HVAC system will be important in determining the type and number of instruments needed for the test. Good coordination with personnel at the test site is vital to the success of the test. Sometimes an advance visit is needed to work out some of these details.

### 3.2.1 Building

First, certain information about the building is needed to plan for the test and select the appropriate instrumentation and protocol details. The size of the building and number of thermal zones helps determine the number of temperature measurements needed. The occupancy schedule and use of the building indicates the extent to which normal operation can be disrupted to install instruments and implement a protocol which may leave the building hotter or colder than usual. Occupancy was kept to a minimum during the test to minimize the occupant impact on the energy

balance and to protect the occupants from the inconvenience or likelihood of interfering with sensor wiring. The location and season influences whether a heating test or an air conditioning test is performed. The materials of construction give an idea of what to expect regarding the building thermal load coefficient and thermal capacitance, which, in turn, helps determine the sequence of temperatures to impose.

Obtaining a copy of the building plans, elevations, and specifications in advance is advised. They can be helpful in terms of preparing a simulation input description, and planning and documenting instrumentation placement.

### 3.2.2    Energy System

The type of air and water distribution system for heating and cooling at the building has an important influence on the required flow and temperature measurements. Electric power monitoring equipment adequate to measure power input to a chiller and a flow meter is necessary. The boiler and chiller (and other equipment) capacities and rating will influence the specific choice of monitoring equipment. It is especially important to determine details of the electric and gas service entrance in advance, because the monitoring equipment must definitely fit the service.

### 3.2.3    Facility Personnel

A primary contact person at the test site was assigned in advance to coordinate scheduling, permission, access to the site, and other details. It is recommended that, if possible, a technician familiar with the details of the building and system provide a tour of the site before the test. An electrical or mechanical contractor at the site may be familiar with the building. It is especially important to contact someone who is familiar with the operation of the HVAC controls.

## 3.3  Instrumentation and Measurements

This section discusses the instruments used during a test and the array of measurements made and includes specific examples from the test sites.

### 3.3.1    HVAC

The energy delivered to (or extracted from) the building by the HVAC system is normally measured directly as part of the STEM test. This usually requires measuring a fluid flow rate (air or liquid, but not refrigerant) and temperature difference of the fluid as it enters and leaves the control volume of interest. The

product of mass flow rate, specific heat, and temperature is calculated by the data acquisition system at short time intervals (10 seconds).

*Air flow rate.*    Two different approaches—the tracer gas system and flow hood measurements—were used to measuring air flow rates in short-term tests.  The tracer gas system is used to measure the supply air and outside air flow rates at an air handler by injecting the tracer gas at one point and sampling at three points. The concentration of tracer gas is sampled:

1.    in the supply air duct after the fan
2.    in the return air
3.    in the mixed (return plus outside) air flow.

The gas is injected at a known flow rate after the mixed air sampling point near the supply fan.  Each sampling station is usually a multipoint array to mitigate the inaccuracies induced by nonuniform mixing of the gas in the air flow stream.  The supply air flow rate can be calculated from the difference in concentration between the mixed air and supply air and the known injection rate.  The outdoor air flow rate can be calculated from the difference in concentration between the return air and mixed air.  The tracer gas system was not directly linked to the data logger usually used to the measure temperature difference, so the product of flow and temperature difference was not readily available.

The other (sometimes simpler) approach to air flow rate measurements is to sample all the diffusers in the building using a flow hood, adding up the flows to get the total supply air flow rate.  This can work in a constant volume system, but not in a variable volume system.  It also gives a measurement of the flow distribution to the zones, which is not available from the tracer gas system.  Experience indicates that this is feasible for buildings of up to 10,000 sq ft.

Occasionally the opportunity arose to use a signal from an existing air flow monitoring device (such as a pitot array) already installed in the system.  This measurement was usually compared to tracer gas or flow hood measurements to verify its accuracy.  For a short-term test, installing instruments that require taking apart the duct work is typically not feasible.

*Liquid flow rate.*    In systems where chilled or hot water flows rates must be measured as part of the energy balance, ultrasonic flow meters temporarily installed on the appropriate pipe were used.  The success of the ultrasonic measurement depends on some of the details of the application such as the pipe size, material, and configuration, and type and contaminants in the fluid.

If flow meters are already permanently installed in the system for energy management or other monitoring, the signal may be recorded directly from these meters with the data acquisition system.

**Temperature difference.**   In addition to flow rate, the temperature difference at a heat exchanger, boiler, chiller, or other device must be measured to determine the energy flow rate. The preferred approach to a temperature difference measurement was to temporarily install a multijunction thermopile. A thermopile directly measures temperature difference, as opposed to making two independent absolute temperature measurements. The number of junctions can be selected to produce an appropriate signal level for the expected temperature difference. In an air flow measurement with a thermopile, the junctions can be arranged in the duct to measure the average temperature. In measuring temperature differences in liquid flows, the use of an existing thermal well or other pipe penetration is preferred. If these are not available, the thermopile can be installed on the outside of the pipe.

### 3.3.2   Electric Power

Electric power is always a fundamental measurement in a STEM test. Electric power is usually a dominant term in the energy balance. It is usually desirable to measure the lighting and plug loads separately from the HVAC components like chillers.

A Hall-effect watt transducer sized for the voltage, current, and phase appropriate for the load was usually used. Power factor can be measured in addition to real power, but PF is usually not a major issue in the analysis. Split-core current transformers and clip-on voltage taps were used.

The details of the electric service components and equipment are important in selecting the appropriate power monitoring equipment. Always check access to the electric service as a top priority during the preparations. If the CTs are too small for the wire or buss bar or too large to fit in the enclosure, the required electric power measurements cannot be made.

### 3.3.3   Zone Temperatures

The air dry bulb temperature in locations around a building was recorded to reasonably represent each thermal zone. The zones may be determined according to thermostat placement, usage, or orientation. More than one temperature measurement per zone may be made.

Single-channel loggers with thermistors or direct-wired thermocouples to a multi-channel data logger were used. Sensors are usually placed near the center of a zone, about 3 to 5 ft above floor level. Sensors should be placed so that direct sun light does not strike them and can be placed inside a radiation shield.

### 3.3.4    Tracer Gas

The heat flow due to net air exchange between inside air and outside air can range from very small to very large in many types of buildings. It is, therefore, very important to measure this heat flow as an important part of the building energy balance. A tracer gas system was used to measure the net air exchange between the inside and outside.

Measuring the air flow rate at the outside air damper is usually not adequate to quantify the net air exchange with the outside. Many buildings have miscellaneous air leaks which result in total air exchange much larger than just the flow at the outside air inlet

The tracer gas system consists of a dosing system and a sampling system. The dosing system includes mass flow controller, gas cylinders, regulators and distribution tubing. The sampling system includes a photo acoustic gas analyzer, a multi-channel computer controlled valve device for sampling from up to eight points, and a lot of sampling tubing.

In a typical deployment, the dosing and sampling system is installed at an air handler. Sulfur hexafluoride is normally used as the tracer gas at working concentrations of about 500 ppb to 20 ppm. The gas is injected into the supply air flow and sampled in the return air. The rate at which air from the building is being lost to the outside can be calculated from the rate of injection and the resulting concentration.

### 3.3.5    Weather Station

Weather station instruments are installed to measure temperature, wind speed, relative humidity and solar irradiance during the test. One Campbell CR10 data logger is usually devoted to the weather station.

**Solar radiation.** Direct normal irradiance and global horizontal irradiance are used as inputs to the simulation program used in the analysis. Global horizontal is straightforward enough to measure directly. Direct normal can be measured directly with a normal incidence pyrheliometer (NIP) or it can be inferred from other measurements. A NIP is expensive, large, heavy, and fragile—and can be unreliable.

Direct normal can also be inferred from a shadow-band horizontal pyranometer measurement. We usually install one or more pyranometers in a vertical orientation in addition to the horizontal orientation and calculated direct normal beam irradiance.

Licor photovoltaic-type pyranometers were used, primarily because they were much less expensive and much easier to install (although admittedly less accurate) than thermopile-type pyranometers such as an Eppley PSP. Licors can be glued to a surface of the building with a silicone glue which can be easily removed. The horizontal pyranometer is usually installed at the highest point of the building. The pyranometers should be located where they will not be shaded.

*Wind speed.* Wind speed is used primarily as a variable in the infiltration model for the building, and is also required input for the BLAST weather file processor. No attempt is made to measure the "undisturbed" wind speed away from the building. We usually measure wind speed with a 3-cup anemometer mounted on a mast 6 to 8 ft above the highest point of the building.

*Dry bulb temperature.* Dry bulb temperature is a fundamental variable in the STEM analysis. It is used to determine the inside-outside temperature difference, which in turn is used to determine the building load coefficient. The outside air temperature is usually measured at three to five different locations around the building and check to see that all sensors indicate about the same reading. All outdoor air temperature sensors are located inside a radiation shield and are usually placed in the shadow of the building (on the north side).

*Relative humidity.* The relative humidity is used in the STEM analysis to calculate sky temperature depression and is a necessary input to the BLAST weather file processor. The accuracy of this measurement is not critical and is usually made with a relatively inexpensive instrument.

### 3.3.6    Data Acquisition System

Two types of data loggers were used for the STEM tests. Single-channel temperature loggers are used to measure zone air temperatures, and can be inconspicuously deployed in occupied spaces. They are pre-programmed to start at a coordinated time and are collected at the end of a test. The data processing is typically done using a spreadsheet.

Campbell CR10 data loggers are used to record sensor inputs in a mechanical room where there are several measurement to be made in close proximity and sometimes to measure zone air temperatures using direct-wired thermocouples.

## 3.4 Case Studies

This section describes some of the specific procedures used for the different buildings. A short description is included for each building; additional building details are provided in Appendix F.

### 3.4.1 Building 7108, Fort Riley, KS

Two short-term tests were performed on a 12,500 sq ft, single-story battalion headquarters building at Fort Riley, KS. The building is approximately rectangular in plan, moderately massive and is divided into 20 offices and other rooms. It is one story tall and has a gabled roof with the ridge along the long axis of the rectangle. The building serves as offices of the commanding officer and his staff, administrative offices, classrooms, and a cryptography facility. Heating or cooling energy for the building is extracted from water that is heated or cooled using a boiler or chiller located in an adjacent building. Distribution of heated or cooled air and ventilation of the building is achieved with a multizone, air-handling unit serving six zones in the building. The first test, 5-9 March 1993, was to evaluate the building in the winter heating mode and to evaluate the STEM test protocol. The second test, 1-8 September 1993, was to evaluate the building in the summer cooling mode. Primary testing was performed over weekends during which the building was nearly unoccupied.

**Specific objectives.** The primary technical objective of the winter season test at Fort Riley was to determine the thermal parameters of the building and its HVAC system. The thermal parameters include the building load coefficient, the effective thermal capacitance, the solar heat gain, and the air infiltration. The HVAC performance is characterized by its net thermal efficiency.

Because this was the first application of a STEM test in a building of this size, a secondary objective was to evaluate the details of the measurement techniques, the success of the specified protocol, and the general logistics of testing a building of this size.

**Test protocol.** The interior temperature of the building was controlled according to a carefully specified sequence during the test. A constant and uniform temperature

was maintained with portable electric heaters during the coheating period. The hot water, which normally provides heating for the building, was turned off during this period. The objective of the test during the coheating period was to obtain nearly steady-state conditions to identify the building load coefficient. Daytime data were used to determine the effects of solar gains. Interior temperatures floated above the coheating set point during solar gain periods. A cooldown period followed the coheating period, during which the electric heaters were turned off and the interior temperature was allowed to float down. The thermal response of the building mass was determined during the cooldown period. The last period in the test protocol consisted of operating the normal heating system during unoccupied hours to maintain a constant and uniform temperature. The net efficiency of the system was determined during this period. The system supply and return fans operated continuously during the coheat, cooldown, and HVAC efficiency periods of the test.

Certain other conditions were enforced regarding the building operation during the test. Miscellaneous and incidental electrical end uses were turned off to the extent possible. All interior lights were turned off in unoccupied rooms. All exterior lights were turned off so that electric power measured at the building service entrance included only power dissipated inside the building. Operable windows were closed. Domestic water heating was turned off. The testers were not allowed access to certain secure areas of the building, so temperature sensors and portable heaters were not deployed in these areas.

***Instrumentation and measurements.*** During the test, temperatures, heat flow rates, air flow rates, and weather conditions were measured. Three Campbell CR10 data loggers were used to collect data from the sensors installed specifically for this test. Sensor input channels were sampled every 20 seconds, and average values were stored every 15 minutes. These loggers are small and portable, and are easy to temporarily install at different locations around the building. Wiring sensors to the data loggers is simplified by having the capability to distribute loggers to different locations. One was installed in the mechanical room to accept the sensors concentrated in this area. The other two were located in offices in the building and served only to measure interior temperatures and to control electric heaters. These loggers could not be deployed in the occupied areas of the building during normal business hours because the sensor wires posed a potential hazard to occupants, and vice versa. They were installed after 1800 on Friday, and removed before 0600 on Monday.

The weather station for this STEM test included one anemometer, two pyranometers, one relative humidity sensor and two or more ambient dry bulb temperature sensors. The anemometer was mounted on the roof of the building at approximately

the height of the ridge. One pyranometer was mounted in a horizontal orientation at the highest point of the roof, and the other was mounted vertically on the east face of the building. The ambient temperature sensors and relative humidity sensors were mounted in shielded enclosures on the north side of the building about 10 ft away from the north wall.

Total electric power supplied to the building was measured with a Dranetz power analyzer. Fifteen-minute average electric power was recorded on paper and later transcribed by hand to electronic media. In subsequent tests there was a separate power transducer connected directly to the Campbell data logger.

Interior air temperature was measured at multiple locations around the building during the coheating and cooldown tests. Temperatures were measured using type T thermocouples mounted in a radiation shield enclosure. Each sensor was located 4 ft above floor level. A temperature sensor was located in nearly every perimeter office. A total of 18 interior air temperatures were measured. A large number of separate measurements is required to characterize the uniformity of the temperature around the building and to adequately determine temperature changes over time. The temperature of air in the plenum space was also measured in two locations.

Net exchange with outside air and HVAC system air flow rate were measured with a tracer gas injection and sampling system. Carbon dioxide was used as the tracer gas, and an infrared detector was used to sample the resulting concentration in this test. Carbon dioxide ($CO_2$) was periodically injected into the air handler near the supply fan. The decay in concentration was continuously sampled by the IR detector in the air handler near the return fan. The net air exchange of the building air with outside air can be calculated from the decay in concentration. Because $CO_2$ is produced by occupants of the building, this technique cannot be effectively used during occupied hours, and was not used in subsequent tests.

Portable electric heaters were installed during the coheating period while the normal heating system was turned off. The heaters were connected to standard 120-volt outlets distributed around the building. Relays controlled by the Campbell data loggers turned the heaters on and off to maintain a constant temperature, depending on the temperature indicated by a thermocouple in the same room as the heater. A small mixing fan was deployed near each heater to help achieve a uniform temperature.

A new device for recording temperatures was tried out during this test. One-channel temperature loggers, called "Hobos," were used to measure interior air temperatures. These devices have the temperature sensor and data logging electronics integrated

into a small package of less than 1 cu in. in volume. These loggers are potentially very useful in STEM tests for commercial buildings because they can be easily and inconspicuously installed in occupied areas. Ten Hobos were installed in Building 7108. They were used to determine the distribution of interior temperatures during occupied periods before the Campbell data loggers were deployed. Several Hobos were located in the same radiation shield enclosures as the standard thermocouples during the coheating test to determine whether the separate reading fell within an expected error band. One interesting finding during this test was that air movement through infiltration and damper leakage provided almost enough ventilation to meet ASHRAE standards. Although adequate ventilation is desirable, infiltration and leakage are not the proper means to achieve it.

**Cooling Season Test Protocol.** A second test at Building 7108 was performed in September 1993. The main objective of testing in the cooling season was to characterize the performance of the air conditioning system. In general, it is not possible to do a coheating test to determine the building load coefficient in the summer because an adequately large temperature difference between inside and outside is usually not feasible. The building response to solar gains and changes in interior temperatures can be estimated in cooling season tests.

Instrumentation was essentially the same as for the winter test. The portable electric heaters were deployed in the building in an arrangement similar to the winter test. The heaters were controlled to introduce a known heat flux in the conditioned space while the building air conditioning system was operated by its normal controls to maintain desired interior space temperatures.

This test revealed a number of problems associated with the building's air conditioning system. For example, the tracer gas measurements indicated an extremely high ventilation rate. This problem was eventually traced to a loose fan belt on the return air fan, which caused outside air to come in through the relief damper. The building's economizer cycle control strategy also was found to function improperly. The strategy required the return air temperature to be above a certain minimum level, but the set points of the room thermostats were just low enough that the return air temperature never reached this threshold.

### 3.4.2    Aspinall-Wilson Conference Center, Gunnison, CO

A short-term test was performed on the Aspinall-Wilson Conference Center, a 9600-sq ft building at Western State College in Gunnison, CO. The building is single story and has extensive vertical and sloped glazing resulting in large solar gains. The building is ventilated by two separate air-handing units serving the east and west

portions. A boiler provides hot water for space heating to individual terminal boxes and also to radiant ceiling panels along the perimeter. The test period, 7-12 October 1993, provided data for evaluating the building in the winter heating mode. No cooling mode tests were performed because cooling is generally not needed during the mild Gunnison summers (at 7700 ft elevation), although the building does have an evaporative cooler. The test was carried out over a weekend during which the building was mostly unoccupied, although data were logged from Wednesday afternoon through Tuesday morning.

The researchers had more success obtaining steady and uniform temperatures in Gunnison than at Fort Riley. Data on either of two nights could be used for the coheating analysis.

***Specific objectives.*** The objective of this test was to determine the thermal parameters of the building and its HVAC system, including the building load coefficient, the effective thermal capacitance, the solar heat gain and the air infiltration. In addition, it was hoped that the STEM test protocol used during the Fort Riley test could be used to verify its application to other commercial-scale buildings and systems. The excessive window area of this building also provided an opportunity to better characterize the solar gain of a building.

***Test protocol.*** The test protocol used for the Gunnison building is very similar to that used for the Fort Riley winter test. The interior temperature was controlled according to the specified test sequence, with heating provided by portable electric heaters. The hot water was turned off, and the fans for both air handling systems were run continuously during the entire test period. A cooldown period followed the coheating period, during which the electric heaters were turned off and the interior temperature was allowed to float down. The thermal response of the building mass is determined during the cooldown period. The last period in the test protocol consisted of operating the normal heating system during unoccupied hours to maintain a constant and uniform temperature. The net efficiency of the system is determined during this period.

Certain other conditions were enforced regarding the building operation during the test. Miscellaneous and incidental electrical end uses were turned off to the extent possible. All interior lights were turned off in unoccupied rooms. All exterior lights were turned off so electric power measured at the building service entrance included only power dissipated inside the building. Domestic water heating was turned off.

***Instrumentation and measurements.*** The instrumentation and measurements of the Gunnison building are similar to those used for the Fort Riley test. Campbell

CR10 data loggers were used to collect the temperature data from the building and control the portable electric heaters. Total electric power supplied to the building was measured with a Dranetz power analyzer and the data collected by another Campbell data logger. The weather station sensors were installed on the roof and recorded using another Campbell CR10.

The weather station included the same equipment used at Fort Riley: two pyranometers, an anemometer, one relative humidity sensor and two or more ambient dry bulb temperature sensors. One pyranometer was mounted horizontally at the highest point of the roof, and the other vertically on the south face of the building. The anemometer was also mounted on the roof of the building. The temperature sensors and relative humidity sensors were mounted in shielded enclosures on the north side of the building.

The interior air temperature was measured at multiple locations around the building using type T thermocouples mounted in a radiation shield enclosure. Each sensor was located 4 ft above floor level. Numerous measurements were made in every area of the building, to characterize the uniformity of the temperature around the building and to adequately determine temperature changes over time.

The portable electric heaters were installed during the coheating period while the normal heating system was turned off, with a small mixing fan near each heater to help achieve a uniform temperature. Relays controlled by the Campbell data logger turned the heaters on and off to maintain a constant temperature of about 72 °F. The control depended on the temperature indicated by a thermocouple in the same room as the heater.

The infiltration was measured by installing the dosing and sampling equipment at both air handlers. The sulfur hexaflouride was injected into the supply air flow and sampled in the return air of both systems.

As with the tests at Fort Riley, several problems were found with the air conditioning system. Most notably, the relief duct was allowing intake of outdoor air rather than discharging return air. This caused a great excess of ventilation air to enter the building. To overcome this difficulty, it was eventually necessary to completely cover the relief outlet so that air-change rates would be more typical. The test also revealed that the discharge air temperature controllers did not seem to be controlling the supply air temperatures to specification. Furthermore, several zones overheated when the heating system was used, indicating a lack of control for some reheat coils and panel heating equipment.

### 3.4.3 Director Building, Portland, OR

The Director Building, an 8-story office building, was tested in November 1994 over the Thanksgiving holiday weekend. The building is a renovated historic building located in downtown Portland, OR. The building renovation in 1987 added a 2-story penthouse to the original 7-story structure, and converted the lower level into a parking garage. The first two floors (ground floor and mezzanine) of the building are primarily retail space. The remainder of the building is office space occupied by a variety of tenants. The building appears to be typical of older multistory structures, with 16 in. to 20 in. thick brick wall and heavy timbers contributing to the mass of the building. The HVAC system is a water-loop heat pump with a gas-fired boiler as its heat source and a cooling tower for heat rejection. There are approximately 93 heat pumps controlled by 93 individual thermostats. Fresh air is intended to be supplied to each heat pump by a separate ventilation system, but can also be supplied to perimeter offices by operable windows.

*Specific objectives.* The primary objective was to evaluate the logistics of using a STEM-based protocol to test a building of this size and configuration. Because STEM was originally developed for testing 1- or 2-story buildings, the results carry implications for the feasibility of using this commissioning procedure on large buildings.

*Test protocol.* Air temperatures were measured in 40 locations inside the building using single-channel "Stowaway" data loggers, similar to the "Hobo" data loggers used at Fort Riley. The intent was to represent the temperatures of five zones on each floor: one core zone plus four perimeter zones. The loggers were distributed during occupied hours and their function was explained to the people in the offices. An attempt was made to locate each sensor where it would not be directly irradiated, but would be exposed to representative conditions near the center of the zone. Each logger was identified by its serial number and the serial number was identified on a copy of the floor plan. The loggers were programmed to start collecting data at the same time at the beginning of the test and were collected at the end of the test. No information on zone temperature was available as the test progressed - a potential weak point of using distributed single-channel loggers.

The objective of the test during the coheating period was to obtain nearly steady-state conditions to identify the building load coefficient. Daytime data are used to determine the effects of solar gains. Interior temperatures floated above the coheating set point during solar gain periods. A cooldown period followed the coheating period, during which all zone heat pump thermostats were turned off and the interior temperature was allowed to float. The thermal response of the building mass is determined during the cooldown period.

Certain other conditions were enforced regarding the building operation during the test. Miscellaneous and incidental electrical end uses were turned off to the extent possible. Interior lights were turned off in unoccupied rooms. Due to the size of this building compared to the others tested, the researchers could not control the interior conditions to the same degree. This, however, should be expected and must be considered when performing a STEM test on any commercial building.

Table 3.1 shows the test sequence for the Director Building. Similar schedules were also developed for the other STEM tests.

**Instrumentation and measurements.** A Campbell CR10 data logger was installed in the penthouse mechanical room to measure the net heat added by the boiler or removed by the cooling tower to the heat pump circulating loop. A type T thermopile was inserted in existing thermal wells to measure temperature difference in the loop and an ultrasonic type flow meter was installed on the pipe to measure the total water flow in the loop. The weather station sensors were also installed on the roof and recorded using another Campbell CR10.

Two pyranometers were installed on the roof of the building, one placed horizontally and the other vertically facing south. The outside dry bulb temperature near the roof was measured with two thermocouples. The dry bulb temperature in the parking garage was also measured with two thermocouples. The outside relative humidity and wind speed were measured near the roof level.

Zone temperatures were measured with Stowaway data loggers. Five Stowaways were deployed on each floor. There were typically one in each of four perimeter zones and one in the core zone of each floor. Average hourly temperatures were recorded beginning by about 1800 on Tuesday. No information on zone temperature

**Table 3.1. STEM Test Sequence - Director Building, Portland, OR.**

|  | Tues 11/22 326 | Wed 11/23 327 | Thurs 11/24 328 | Fri 11/25 329 | Sat 11/26 330 | Sun 11/27 331 | Mon 11/28 332 | Tues 11/29 333 |
|---|---|---|---|---|---|---|---|---|
| Normal Operation | ---------- | -------- |  | (retail) | (retail) |  | ------- | ------- |
| coheat |  | -- | ---------- | ---------- | ---------- |  |  |  |
| cooldown |  |  |  |  |  | ---------- |  |  |
| install instruments | ---- |  |  |  |  |  |  |  |
| install tracer gas |  | -- | --- |  |  |  |  |  |
| remove tracer gas |  |  |  |  |  |  | --- |  |
| remove instruments |  |  |  |  |  |  |  | --- |

was available during the test because the researchers were not allowed to check the loggers during the test. Loggers were typically left in the same location during the entire test period. Ten loggers were deployed on October 21, approximately one month before the test, to get a preliminary indication of spatial and temporal temperature variations in the building.

The main service entrance power to the building was measured, starting on 22 October. Power to retail spaces was measured separately. The exterior power included in the total measurement was later estimated in an audit, and taken into consideration when evaluating the total building energy demand.

The total water loop flow rate was measured with an ultrasonic flow meter. This flow rate was found to be approximately constant. The temperature difference across the combination of the cooling tower and boiler in the mechanical room was measured with a thermopile. No other fluid temperatures or flow rates were measured.

The building manager was asked to assure that no night set back would be implemented through the winter starting on 1 November, which would also include the test period. All thermostats were checked on Tuesday night and Wednesday night to verify that they were set near 72 °F for heating. Cooling set points were verified to be at or above 80 °F. The thermostats were not adjusted during the coheating test to correct minor temperature differences between zones (plus or minus 5 °F). The objective with this building was to keep all zones in the building within the same temperature range, and not significantly disturb the normal operation of the building. Also, most of the occupants were asked before the test period to keep their thermostats set in the normal operation temperature range and not set them back for the holiday. The cooldown was initiated by turning the zone heat pump thermostats off. Because of the size of the building, this took approximately one hour. Storage room thermostats were not changed.

The air source heat pump for the water loop was turned off. All loop heating was to be accomplished by the boiler. The cooling tower was not expected to operate. All interior lights were turned off to the extent possible, realizing that in an 8-story office building complete control of this is not realistic.

The original plan was have the tracer gas equipment completely installed by 0000 Thursday and use all of Thursday to try to achieve a uniform concentration in the building. By injecting the tracer gas to only the first and second floors and measuring concentrations on the 6th, 7th, and 8th floors, the researchers hoped to determine the appropriate placement of injection and sampling points on each floor.

Two injection points and two sampling points for each floor were planned, requiring about 80 leak-free connections. The injection and sampling points could be moved around on the same floor to determine whether the concentration is uniform within a zone. Four mass flow controllers were available, and would be used to attempt to achieve a uniform concentration across all zones. The tracer gas, however, did not arrive until Friday afternoon, delaying the process by more than a day. The protocol detailed above was still used, although within the remaining limited time frame.

Regardless of the disruption of the testing sequence described above, the researchers were able to conclude that there appear to be no serious logistical obstacles to using STEM-based energy testing on a multistory office building. However, it is clear that larger buildings, as compared to smaller ones, pose additional challenges in terms of systems and occupancy control.

### 3.4.4    Bell Avenue School, Sacramento, CA

STEM tests were performed on a portion of an elementary school located near Sacramento, California in December 1994. The building selected for testing was one wing of the Bell Avenue Elementary School, a single-story, rectangular structure consisting of four adjoining classrooms. The school was built about 1960 and is typical of many schools of similar age in California. The interior floor area covers about 4,300 sq ft. Each classroom is heated and cooled by a residential-type furnace and air conditioning unit, which are controlled by thermostats in each room. An energy management system turns the system off after occupied hours. The winter test was performed at the beginning of the Christmas holiday period during which the school was completely unoccupied.

**Specific objectives.** The Sacramento Municipal Utility District and local school districts are interested in evaluating the potential effect on peak electric loads and costs of extending the local school year from nine months to twelve months. The results of the STEM tests can help predict the expected increase in air conditioning use during the summer months. The approach for this building was to perform a winter test to characterize the thermal parameters of the building. Summer tests would then be performed to evaluate the standard air conditioning performance and the performance of alternative technologies.

**Test protocol.** A standard STEM test was performed in 15-21 December 1994. The test included a coheat, cooldown, and furnace operation period, with protocol details similar to those for the Fort Riley and Gunnison buildings.

Table 3.2 describes the schedule for the entire winter test sequence at the Bell Avenue school.

*Instrumentation and measurements.* The monitoring instruments used to measure the performance were essentially the same as for a standard residential test. A standard weather station including horizontal and vertical solar radiation, wind speed, relative humidity and dry bulb temperature was installed. Electric power for the entire wing was measured at one point. Two shielded air temperatures were measured in each classroom. Four portable electric heaters were installed in each room for coheating, along with portable fans to help achieve uniform temperatures. Air infiltration for each room was measured with a tracer gas system.

**Table 3.2. Two-week STEM test schedule - Bell Avenue School, Sacramento, CA.**

|  | Sunday Dec 11 345 | Monday Dec 12 346 | Tuesday Dec 13 347 | Wednsday Dec 14 348 | Thursday Dec 15 349 | Friday Dec 16 350 | Saturday Dec 17 351 |
|---|---|---|---|---|---|---|---|
| get rental car |  | --- |  |  |  |  |  |
| pack gear |  | ----- |  |  |  |  |  |
| drive to Sacramento |  |  | --------------- | ----------- |  |  |  |
| get access |  |  |  | -- |  |  |  |
| presentation at SMUD |  |  |  |  | ------- |  |  |
| install weather station |  |  |  |  | --- |  |  |
| install electric power |  |  |  |  |  | ----- |  |
| install inside temps |  |  |  |  |  | ----- |  |
| install heaters |  |  |  |  |  | ----- |  |
| install tracer gas |  |  |  |  |  | ----- |  |
| coheat |  |  |  |  |  | ---- | -------------- |

**Table 3.2. Continued**

|  | Sunday Dec 18 352 | Monday Dec 19 353 | Tuesday Dec 20 354 | Wednsday Dec 21 355 | Thursday Dec 22 356 | Friday Dec 23 357 | Saturday Dec 24 358 |
|---|---|---|---|---|---|---|---|
| coheat | --------------- | --------------- |  |  |  |  |  |
| cooldown |  |  | ----- |  |  |  |  |
| furnace operation |  |  | ----------- | ----- |  |  |  |
| end of test |  |  |  | -- |  |  |  |
| pack equipment |  |  |  | --- |  |  |  |
| drive |  |  |  | ------- | --------- |  |  |
| presentation, training |  |  | --- |  |  |  |  |

# 4   Base Model Development and Optimization

After collecting the data using the STEM protocol, the objective was to develop a
building model that accurately simulated the total energy performance of the con-
structed building.  First, a base building model was created from the building plans,
incorporating into this model the ability to easily vary a selection of physical building
parameters, such as the roof and wall insulation R-values or window transmittance.
By varying select parameters that influence the performance of the building, and
incrementally changing the simulation model, a final simulation building that best
models the total annual energy performance of the building was achieved.

## 4.1   Base Building Description

A base building model was first created from each building's original building plans
plus observations made during the STEM test.  This included creating a weather file
from the measured weather data, and creating infiltration schedules and indoor
temperature control schedules from measurements made during the test period.  The
infiltration was used to best simulate the actual air flow through the building, and
was distributed evenly, based on zone volume, so that each zone experienced the
same number of air changes per hour.  The measured indoor air temperatures were
used to drive the BLAST simulation, from which the total energy required to achieve
those temperatures was generated.  Total energy demand required by the building
model was compared with the measured energy demand, changing the building
model parameters to achieve the best match between the two.

Before beginning the actual analysis by changing the base building parameters, we
verified that the simulated building energy demand showed at least a rough
similarity to the measured building energy demand.

## 4.2   Data Comparison Window

Initially, the researchers expected to analyze each parameter variation during
different comparison windows based on the parameter itself.  For example, the
energy demand generated by a BLAST simulation while changing the exterior

insulation values would be compared to the measured building load late at night when the solar and lighting heat effects would be at a minimum. Other parameters influencing the effects of solar heat on the building, such as window transmittance, would be compared during periods of high solar gain. However, during the STEM testing period the researchers were unable to control all of the variables influencing the building. For instance, during the test in Gunnison, CO, interior lights were necessary during various periods, including nights, to provide additional energy for maintaining the desired set-point temperature. In Building 7108 several lights were always on because of its twenty-four-hour occupancy. In addition, there was no control over the building occupants or their activities during the test, and the buildings were rarely unoccupied through the entire test period—even over the holidays.

Another aspect of the data comparison window affected the decision. Initially, window transmittance was evaluated only during the day, based on the influence windows have on solar gains. The solar gains, however, not only influence the building during the daylight hours, but strongly influence the building performance after sunset when the energy stored in the building's mass is transferred to the air. The primary difficultly came from trying to accurately determine the hours during which the changing building characteristics most strongly influenced the energy performance, and whether isolating each parameter's influence to a single window of time could be justified.

Given the lack of strong justification for "windowing," the researchers chose to calculate the rms error between BLAST simulated data and measured data for all parameter variations over the same time span. Selecting this comparison period is a judgment based on when the simulated data best approaches both the shape and magnitude of the measured energy demand curve. Figure 4.1 shows the measured energy demand and the base building simulated energy demand for the Bell Avenue School. This plot also shows the average measured indoor temperature during this time. The researchers chose to start the comparison at 1000 hours Saturday and compare the data for 72 hours until 1000 Tuesday. The purpose was to be able to match the measured energy during the initial heat up of the building, during the constant temperature period, and during the cooldown on Tuesday morning.

Seventy-two hours provided 3 full days of comparison and allowed the researchers to analyze the results over a range of inside and outside conditions.
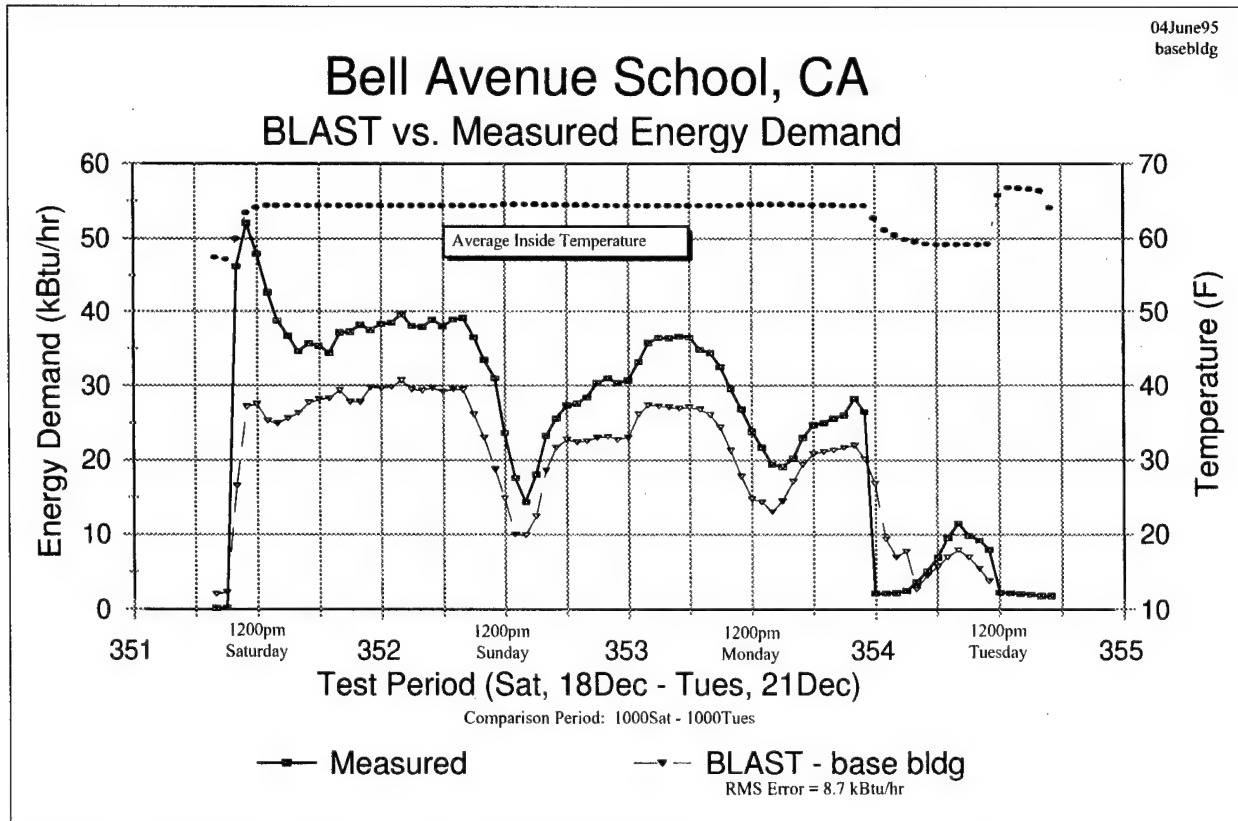
Figure 4.1. Simulated vs measured energy demand for Bell Avenue School base model.

## 4.3 Error Calculations

The rms error between the measured and simulated energy demand was chosen as one metric for comparing the results. The rms error (RMSE) is given by

$$RMSE = \sqrt{\frac{\Sigma(Energy_{measured} - Energy_{BLAST})^2}{n}} \qquad \text{[Eq 1]}$$

where n is the number of hours in the comparison period. Using this metric, the researchers first determined the error between the energy demand generated by a BLAST simulation of the model and the measured values from the real building. This base building rms error was then used as a guideline to optimize the building model.

For each iteration during the analysis, selected building parameters were each varied from 10 percent to 200 percent of their minimal audit value and for each value a BLAST simulation performed. An rms error was calculated for each variation of each parameter, indicating the change in building model with respect to the

measured energy demand. The minimum rms error for each parameter was determined, and from these the overall minimum error selected.

Each iteration, referred to as a run, indicates one complete series of parameter variations all starting with the same building model. For example, Run 1 refers to the series of parameter variations performed on the base building model. From Run 1 results, one parameter is changed in the BLAST building input file, providing a modified building model to be used for the next run. Run 2 then refers to the series of parameter variations on the modified building model resulting from Run 1. Table 4.1 shows an example of rms error results for seven different parameters of the Bell Avenue School. These are results for Run 6 of the analysis, indicating that five parameter changes were already made to the base building model.

For this run, the rms error was calculated for varying window transmittance (TEST-GLASS), roof insulation R-value (ROOFINS), internal mass surface area (DIMEN-SIONS), exterior wall thickness (BLOCK1 L) and thermal conductivity (BLOCK1 K), and internal mass thickness (BLOCK2 L) and thermal conductivity (BLOCK2 K). Each parameter was varied from 10 percent to 200 percent of its minimal value, except window transmittance, which was varied from 10 percent to 110 percent of its minimal value. For each parameter, the minimum rms error and the percent of the minimal value which generated that error are shown in the second to last row of the table. The last row indicates the change in the rms error for that parameter from the minimal case (100 percent) for that run. For example, column five of Table 4.1 shows the rms error calculated from varying the roof insulation R-value from 10 percent to 200 percent. The minimum error between the simulated building energy demand and the measured values is 3.77 kBtu/hr. This is also the error for 100 percent of minimal roof insulation, so the last row is zero. Changing the roof insulation R-value or the internal mass surface area from their minimal values at this point would provide no improvement in terms of matching the energy demand of the model to that of the actual building.

On the other hand, changing the internal mass thickness to 60 percent of its minimal value would reduce the rms error by 2.1 percent. The greatest error reduction (2.9 percent) is found for the building model with 30 percent of minimal window transmittance. So, based on these results, window transmittance in the modified BLAST input deck[*] was changed to 30 percent of its minimal value and repeated the BLAST simulations for the next run, varying all the parameters again.

---

[*]  input deck: a BLAST input file. This terminology has been retained from the days when data were input into BLAST using a "deck" of punch cards.

Table 4.1. Array of RMS errors (kBtu/hr) between simulated and measured energy demand.

| Sacramento | TESTGLASS | | ROOFINS | | DIMENSIONS | | BLOCK | | BLOCK | | BLOCK | | BLOCK |
| 06June | TRANS | fraction | R | fraction | INTMA | fraction | L | fraction | K | fraction | L | fraction | K |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| run 6 | | | | | | | | | | | | | |
| 0.1 | 3.674 | 0.1 | 13.064 | 0.1 | 6.271 | 0.1 | 6.255 | 0.1 | 7.128 | 0.1 | 4.677 | 0.1 | 4.145 |
| 0.2 | 3.667 | 0.2 | 10.680 | 0.2 | 5.807 | 0.2 | 5.415 | 0.2 | 6.087 | 0.2 | 4.326 | 0.2 | 3.997 |
| 0.3 | 3.662 | 0.3 | 8.874 | 0.3 | 5.374 | 0.3 | 4.781 | 0.3 | 5.426 | 0.3 | 4.048 | 0.3 | 3.918 |
| 0.4 | 3.667 | 0.4 | 7.382 | 0.4 | 4.986 | 0.4 | 4.355 | 0.4 | 4.903 | 0.4 | 3.854 | 0.4 | 3.873 |
| 0.5 | 3.675 | 0.5 | 6.226 | 0.5 | 4.641 | 0.5 | 4.053 | 0.5 | 4.471 | 0.5 | 3.759 | 0.5 | 3.841 |
| 0.6 | 3.688 | 0.6 | 5.334 | 0.6 | 4.342 | 0.6 | 3.883 | 0.6 | 4.224 | 0.6 | 3.692 | 0.6 | 3.819 |
| 0.7 | 3.709 | 0.7 | 4.671 | 0.7 | 4.059 | 0.7 | 3.778 | 0.7 | 4.025 | 0.7 | 3.699 | 0.7 | 3.802 |
| 0.8 | 3.734 | 0.8 | 4.208 | 0.8 | 3.886 | 0.8 | 3.738 | 0.8 | 3.913 | 0.8 | 3.708 | 0.8 | 3.790 |
| 0.9 | 3.749 | 0.9 | 3.919 | 0.9 | 3.837 | 0.9 | 3.741 | 0.9 | 3.846 | 0.9 | 3.733 | 0.9 | 3.780 |
| 1 | 3.772 | 1 | 3.772 | 1 | 3.772 | 1 | 3.772 | 1 | 3.772 | 1 | 3.772 | 1 | 3.772 |
| 1.1 | 3.796 | 1.1 | 3.780 | 1.1 | 3.809 | 1.1 | 3.862 | 1.1 | 3.765 | 1.1 | 3.817 | 1.1 | 3.765 |
| | | 1.2 | 3.824 | 1.2 | 3.876 | 1.2 | 3.919 | 1.2 | 3.778 | 1.2 | 3.904 | 1.2 | 3.760 |
| | | 1.3 | 3.937 | 1.3 | 4.007 | 1.3 | 3.983 | 1.3 | 3.804 | 1.3 | 3.950 | 1.3 | 3.755 |
| | | 1.4 | 4.082 | 1.4 | 4.149 | 1.4 | 4.049 | 1.4 | 3.839 | 1.4 | 3.996 | 1.4 | 3.750 |
| | | 1.5 | 4.308 | 1.5 | 4.325 | 1.5 | 4.117 | 1.5 | 3.881 | 1.5 | 4.038 | 1.5 | 3.747 |
| | | 1.6 | 4.474 | 1.6 | 4.408 | 1.6 | 4.168 | 1.6 | 3.926 | 1.6 | 4.078 | 1.6 | 3.743 |
| | | 1.7 | 4.664 | 1.7 | 4.464 | 1.7 | 4.228 | 1.7 | 3.975 | 1.7 | 4.117 | 1.7 | 3.741 |
| | | 1.8 | 4.848 | 1.8 | 4.577 | 1.8 | 4.322 | 1.8 | 4.024 | 1.8 | 4.155 | 1.8 | 3.744 |
| | | 1.9 | 5.054 | 1.9 | 4.684 | 1.9 | 4.367 | 1.9 | 4.088 | 1.9 | 4.189 | 1.9 | 3.741 |
| | | 2 | 5.212 | 2 | 4.806 | 2 | 4.456 | 2 | 4.139 | 2 | 4.222 | 2 | 3.739 |
| minimum ***** | ***** | ***** | ***** | ***** | ***** | ***** | ***** | ***** | ***** | ***** | ***** | ***** | ***** |
| RMS err 30% | 3.662 | 100% | 3.772 | 100% | 3.772 | 80% | 3.738 | 110% | 3.765 | 60% | 3.692 | >200% | 3.739 |
| %smaller 2.92 | 2.92 | | 0.00 | | 0.00 | | 0.89 | | 0.18 | | 2.12 | | 0.86 |

Figure 4.2 shows the rms error curve generated by varying the window transmittance from 10 percent to 110 percent for the previous example. Similar curves exist for the other parameters as well.

In some cases, selecting the parameter that gives a minimum rms error is not as clear cut as the above example. An array of rms errors may indicate a minimum at or greater than 200 percent of the minimal parameter value. For example, from Table 4.1, the minimum rms error for varying the internal mass thermal conductivity occurred for a value greater than 200 percent of the minimal. The researchers ignored this case because it did not provide the lowest rms error for that specific run. However, for some runs 200 percent of a parameter value did provide the minimum rms error. That parameter was doubled in the BLAST input deck and the next run started. In these cases, the parameter value providing the minimum rms error was not typically at 200 percent of the minimal value. Figure 4.3 shows an example of this. Changing the internal mass surface area to 200 percent of its minimal value was not the minimum error for that parameter. However, after several additional iterations and parameter changes, a clear minimum was found in the rms error curve at around 616 percent of minimal surface area. This appeared to be the result for parameters that were underestimated in the base building model. Further discussion is provided in Chapter 5.
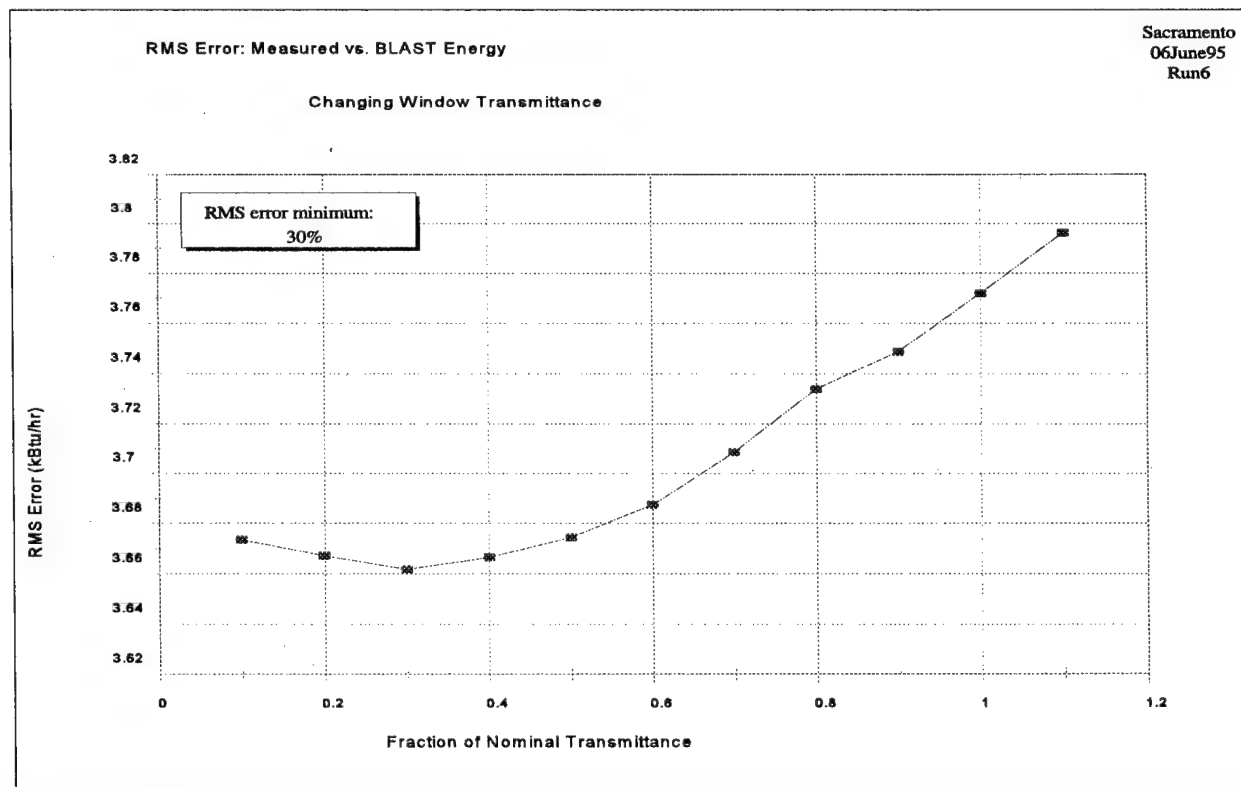


**Figure 4.2. Minimum rms error at 30 percent of minimal window transmittance.**

RMS Error: Measured vs. BLAST Energy

Changing Internal Mass Surface Area
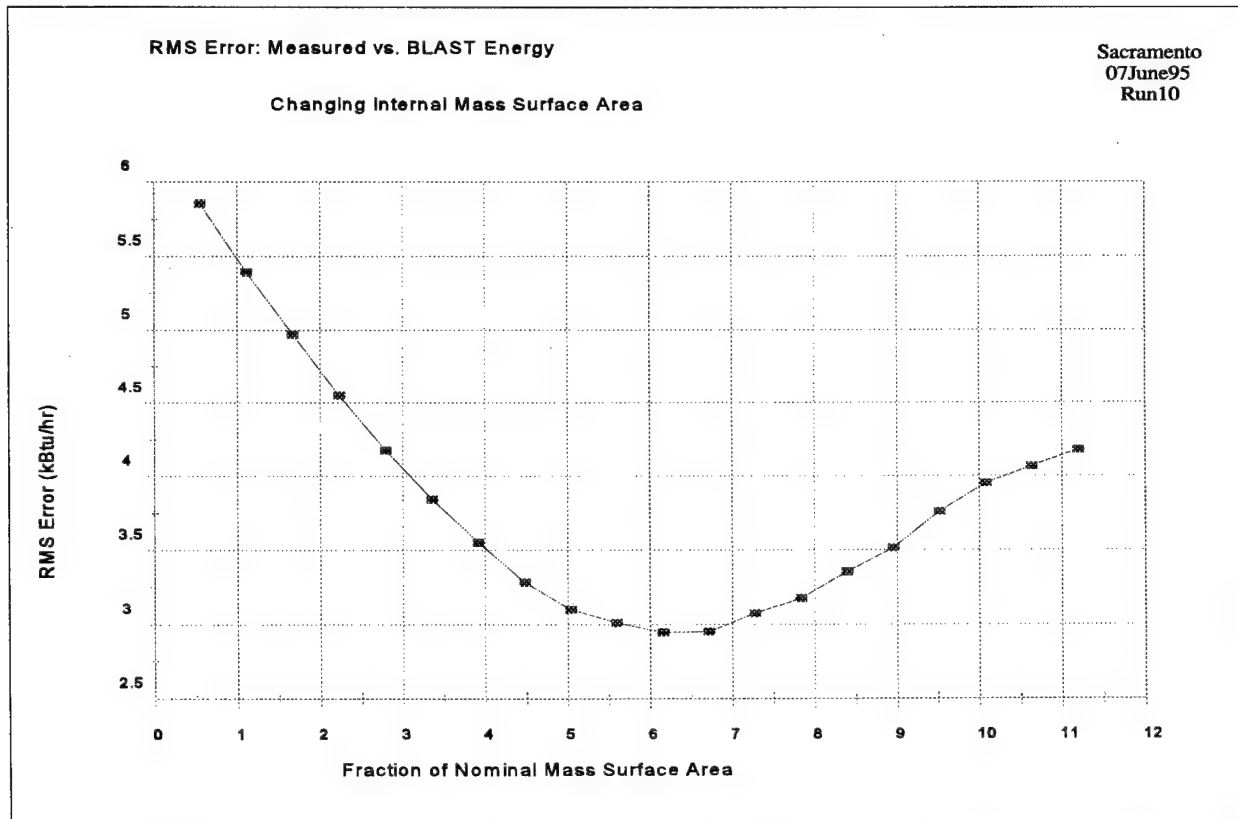
**Figure 4.3. RMS error minimum for parameter value greater than 200 percent of minimal for Bell Avenue School.**

During the analysis the researchers also observed the variation in total energy used by the building model versus the actual building over the comparison period. An R metric was used, which is given by:

$$R = \Sigma(Energy_{measured} - Energy_{BLAST})$$
[Eq 2]

With this, the difference between the total measured and simulated energy demands was calculated for the results of each run. Positive R indicated that the actual building used more energy over the comparison period; negative indicated that the simulated building model used more. This metric was primarily used to verify that the simulated energy demand not only followed the daily pattern of measured energy demand, but also approximated the same total energy use in the specified time period.

## 4.4   Adjusting Parameter Values

To develop an accurate model of the building, a selection of physical parameters in the base model was varied over a range of values. Either four or five primary parameters, including building insulation (wall and roof R-value), window transmittance and internal mass surface area and thickness, were used because of their impact on building energy performance. Four primary parameters were used in buildings with insulation contributing most to the R-value in both the roof and walls. In this case, building insulation was treated as one parameter and all R-values varied simultaneously. Five primary parameters were used in buildings without wall insulation, where concrete block or other material contributed most to the wall R-value and insulation contributed most to the roof R-value. In this case, the building insulation components were varied as separate parameters. The R-value of the wall was varied by changing the concrete block thickness and the R-value of the roof by changing the insulation R-value. The selection of secondary parameters was based on characteristics of the constructed building, such as interior wall and floor solar absorptivity for buildings with many windows or thermal conductivity of the internal mass for buildings with massive internal surfaces.

The following text demonstrates the optimization procedure used for this program. For the purposes of this explanation, we will consider only four primary parameters: building insulation, window transmittance, internal mass thickness, and internal mass surface area. In the actual simulations, we also used any number of secondary parameters.

For each run of the analysis, all four parameters in the input file would be varied, one at a time, from 10 percent to 200 percent of its minimal value in 10 percent increments. BLAST would then be used to simulate the results for each change, noting that the other parameters have been held at their minimal value. With 19 simulations to cover the desired range for each of the four parameters, this would be a total of 76 BLAST simulations. For each simulation the researchers would calculate the rms error, which would indicate the difference between the predicted energy use from the BLAST program and the measured energy use in the field. This series of simulations and rms error calculations is referred to as a run. The goal for each run is to determine the minimum rms error for each parameter, and then the overall minimum for that run.

For example, the first step might be to vary the building insulation R-value from 10 percent to 200 percent of its minimal value in 10 percent increments. Then BLAST would be used to simulate the building performance for each of these changes while holding the other three parameters constant. From these 19 simulations, the

researchers would calculate 19 rms errors and identify a minimum error corresponding to one of the values for that parameter (such as 120 percent of the minimal insulation R-value).

Having determined the minimum rms error for the insulation R-value, the researchers would return it to its original value and complete 19 more simulations while varying the next parameter, such as the window transmittance. The minimum rms error and the value for which that error is generated would also be found for the next parameter. The process would be repeated two more times, with changes made to the internal mass thickness and the internal mass surface area.

Based on these 76 simulations, the researchers would determine which value for which of the four parameters produced the smallest rms error. For the purposes of the explanation, assume that changing the window transmittance to 80 percent of its minimal value produced the smallest rms error from all 76 simulations. The researchers would then change the window transmittance value in the BLAST input deck to 80 percent of its minimal value, retaining the original minimal values for the other three parameters. The modified building model input file is then used to start the next set of 76 simulations, otherwise referred to as the next run.

This entire process of 76 simulations would be repeated many times, each time determining which value for which of the four parameters produced the smallest rms error and adjusting that parameter in the BLAST input file to the new minimal value. This process would continue until the rms error changed by less than 2 percent from the preceding value. During the entire building calibration, it might be necessary to change the minimal value for some parameters more than once.

## 4.5  Convergence Criteria

By varying parameters of the base building model, a modified building model for which the energy performance approached that of the real building was developed. With each iteration, the simulated energy demand approached the same pattern of use as the measured energy demand. However, to avoid a lengthy and tedious process, the researchers stopped the analysis when the change in rms error from the minimal value of a run to the minimum rms error from the parameter variations in that run was less than 2 percent. During the development of this program, it became clear that changes around 3 percent were still significant in terms of matching the shape of the simulated energy demand to the measured demand curve, while changes around 1 percent provided little advantage in better simulating the energy performance of the real building. The 2 percent change typically coincided with changes in

rms error of less than 1 percent from the base building error to the minimum error of a run.

## 4.6 Automation of Building Modeling Process

Running a single simulation of a building model using BLAST is a fairly quick procedure. However, changing even a single parameter many times and collecting the data for comparison can be tedious and time-consuming, in addition to requiring large quantities of computer memory. For this reason, PERL scripts were used to automate the simulation, data collection, and comparison processes. PERL (Practical Extraction and Report Language) was originally designed to assist the Unix user with common tasks not conveniently achieved using the shell and too complicated to code in C or some other Unix tool language (Schwartz 1993). PERL was also made available for use in MS-DOS*, and this version was used for this program.

With PERL the researchers were able to change any specified parameter, invoke BLAST to simulate the modified input deck, collect the data, and compare it to the measured data to calculate the rms error. A table was then compiled for each run, collecting the selected parameter names, the fraction of the minimal value used for a simulation, and the rms error. These tables were easily imported into a spreadsheet, where the minimum rms error and the value of the parameter to be used for the next run was determined. Using the spreadsheet, the researchers also plotted the rms error curves and the energy curves generated by the desired BLAST simulations.

A complete procedure for using PERL to calibrate the BLAST building models—including the PERL scripts—is given in Appendices A–E.

---

\* MS-DOS: Microsoft Disk Operating System, a registered trademark of Microsoft Corp., Redmond, WA.

# 5  Results and Discussion

Each building presented its own challenge in terms of selecting parameters and making assumptions about the building model. While performing the parameter variations to minimize the rms error, various trends in the rms error curves and building model energy performance were encountered. These are explained in this section.

## 5.1  RMS Error Minimum: Observed Fraction vs Curve Fit

During the process of minimizing the rms error, two approaches were followed to determine the parameter variation for the next run. For the first approach—approach A—the fractional value of the parameter directly indicated by the minimum rms error was selected for the next run. An example of this can be seen in Table 4.1 (see Chapter 4), where the window transmittance was changed to 30 percent of its minimal value as indicated by the minimum rms error for that run. This is referred to as the observed or selected minimum fraction. For approach B, the researchers fit a curve to three or four points near the observed fraction and calculated the minimum.

An example of a curve fit is shown in Figure 5.1, which shows the variation of rms error with internal mass surface area for the Sacramento building. The observed fraction from the minimum calculated rms error is around 560 percent of the minimal value. A second-order curve fit to the data indicates a minimum at 537.8 percent of minimal. This comparison illustrates the variability between the two approaches. A discussion of the large increase in internal mass surface area for the Sacramento building is provided below in section 5.2.1.

Both approaches were followed using several buildings to establish whether the final results were comparable, and whether one method was better in terms of simplicity and time savings.

Results from approach A and B are shown in Figures 5.2 and 5.3, respectively, for the Sacramento school building. The figures show the optimized building energy demand compared to the base building and measured energy demand. In general,
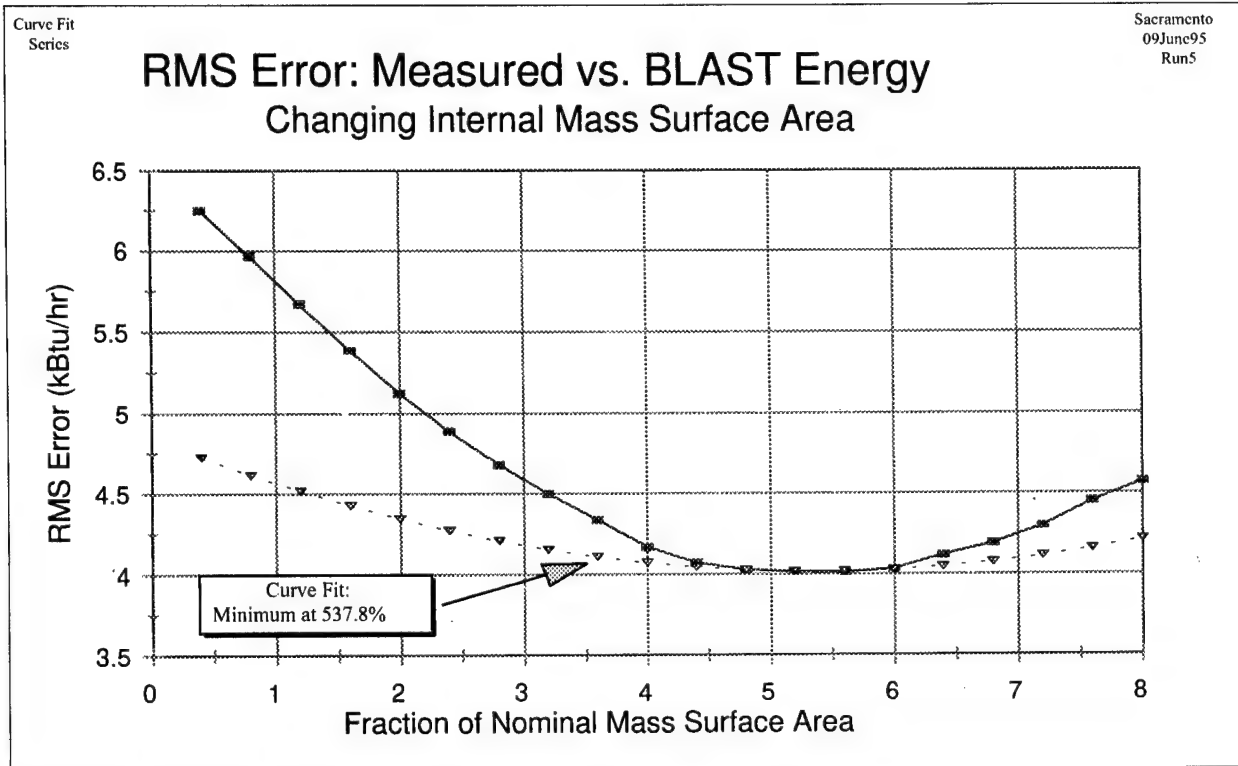
**Figure 5.1. Curve fit to variation of rms error with internal mass surface area.**
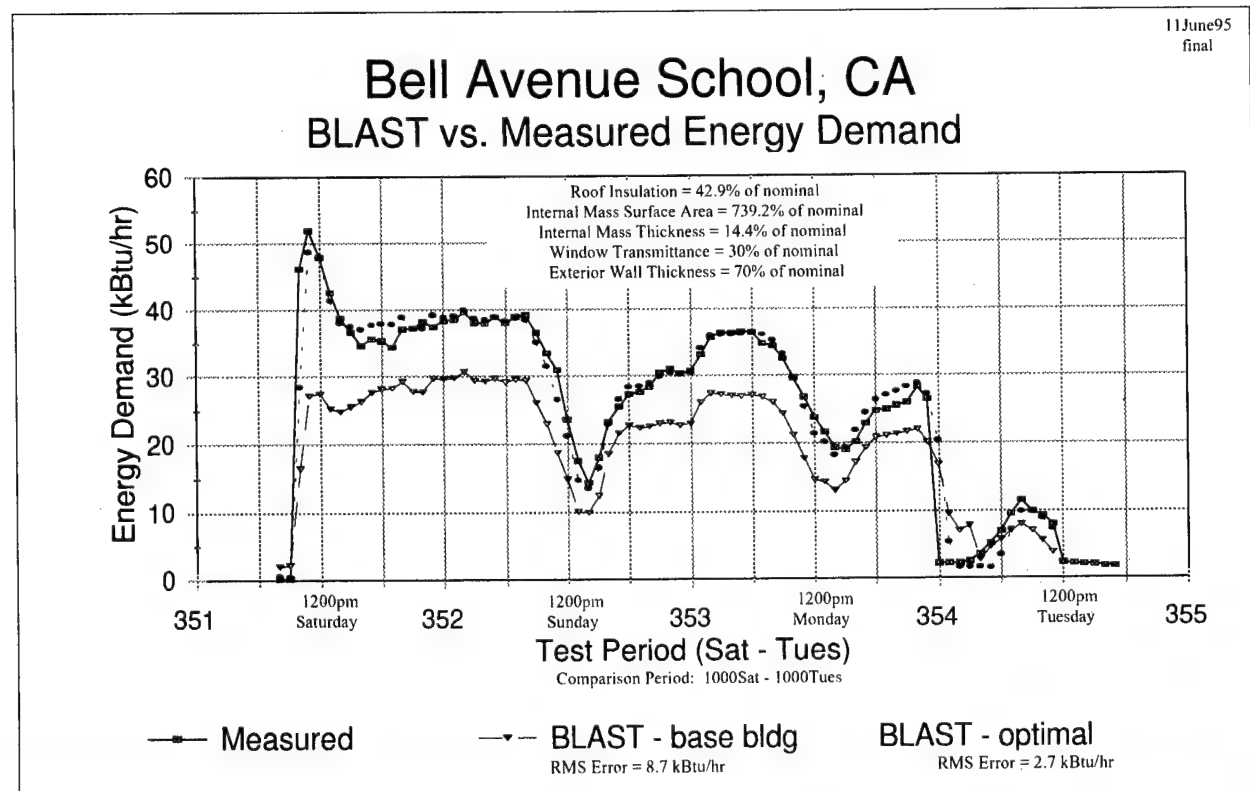


**Figure 5.2. Final simulation results for Sacramento Building using observed fraction approach.**
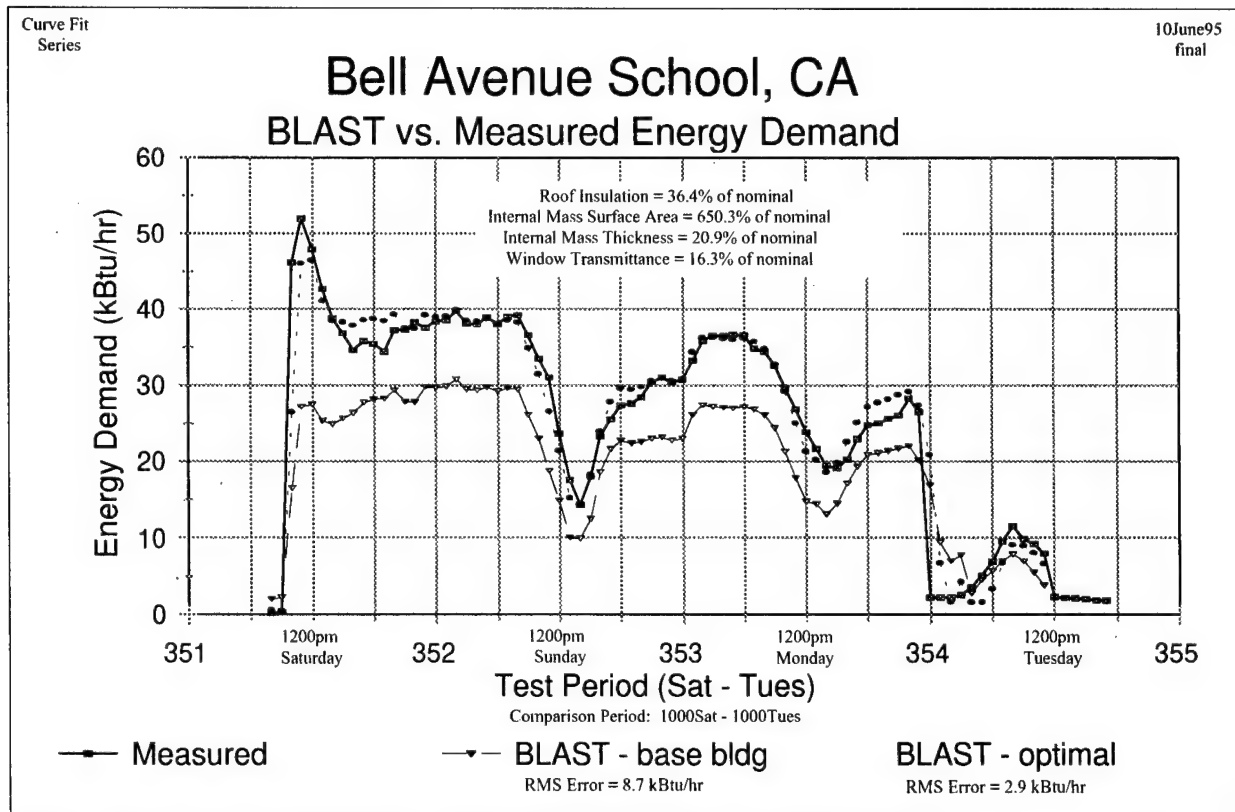
**Figure 5.3. Final simulation results for Bell Avenue School using curve fit approach.**

the shape of both resulting simulated energy demand curves and the measured demand curve are similar. Also, the parameter variations indicated in the figures followed the same increasing and decreasing trends. The observed fraction approach required 13 iterations before the rms error changes met the convergence criteria, and the curve fit approach required 10 iterations.

Both approaches reduced the rms error by more than 60 percent from the base building model, achieving an rms error about 10 percent of the average energy demand over the comparison time period. The final rms error found using Approach A was 2.67 kBtu/hr, and from using Approach B was 2.94. The difference between the final rms errors is less than 10 percent. (See end of section 5.2 for complete results.) The primary difference between the final simulated curves occurs at sharp changes in the measured demand. The final curve generated using the selected minimum from the rms errors matched the sharp energy changes better, contributing to the lower rms error. Because a lower rms error is desirable, the selected fraction approach was chosen (Approach A), and this also provided the better fit over the entire comparison period.

Table 5.1 shows the final fractional change of each parameter for both methods. In both cases the roof insulation R-value, internal mass thickness, and window trans-

Table 5.1. Final fractional values of building model parameters—observed fraction vs curve fit approach.

| Modified Parameter | Final Fraction-Observed Fraction Approach | Final Fraction-Curve Fit Approach |
|---|---|---|
| Roof Insulation R-value | 0.429 | 0.364 |
| Internal Mass Surface Area | 7.39 | 6.50 |
| Internal Mass Thickness | 0.144 | 0.209 |
| Window Transmittance | 0.300 | 0.163 |
| Exterior Wall Thickness | 0.700 | 1.000 |
| *Final rms Error* | *2.67* | *2.94* |

mittance all decreased, while the internal mass surface area increased. The exterior wall thickness decreased for the first approach but not for the second. This thinner exterior wall, however, in combination with the decreased roof insulation R-value, appears to compensate for the lower final roof insulation R-value from approach B. Also, while the trends were the same, the magnitude of the changes varied. The final window transmittance using the curve fits is about 45 percent less than the observed fraction approach, the roof insulation alone about 15 percent less, the internal mass surface area about 12 percent less, and the internal mass thickness is about 25 percent greater. In general, however, the end result from both approaches was similar.

Using both approaches to model the Aspinall-Wilson Conference Center in Gunnison, CO provided somewhat different results. First, the observed fraction approach required nine iterations before the convergence criterion was met, and the curve fit approach required only three. The rms errors were 7.6 kBtu/hr and 9.1 kBtu/hr, respectively, a 17 percent difference. Approach A resulted in a final error of about 12.6 percent of the 54-hour average measured energy demand, and approach B about 15 percent. This may indicate that the base building model fairly accurately simulated the real building performance to begin with.

Using both approaches to model the other building revealed the same trends. Although the curve fit approach required fewer iterations, the final rms error was not as low as that for the observed fraction approach. The final results shown for each building were generated using the observed fraction approach.

## 5.2  Simulation Results

The systematic approach described in Chapter 4 is presented here in detail for the three buildings.  Because the Bell Avenue School had the simplest construction and the most straightforward analysis, these results are presented first and in the greatest detail.  Variations in rms error with each changing parameter are shown, and discussion is offered on the influence that each modified parameter had on the simulated energy demand curve.  Not every building responded in the same way, and the differences are discussed for the respective building.

### 5.2.1  The Bell Avenue School Simulation

The base building model for the Bell Avenue School was somewhat difficult to create because the original building plans were not available.  Therefore, the materials and construction parameters used to model the building are based on the judgment and experience of the individuals performing the STEM test.  Refer to Appendix F for details of the observed construction.

From the base construction, five primary parameters (roof insulation, exterior wall thickness, window transmittance, internal mass surface area, and internal mass thickness) and two other parameters (the exterior wall and internal mass thermal conductivity) were varied.  All parameters were varied from 10 percent to 200 percent of their minimal values, except the window transmittance, which was varied from 10 percent to 110 percent.  The maximum possible transmittance of solar radiation through a glazing is 1.0, indicating that all radiation is transmitted.  The base building window transmittance is 0.87.  When varying in 10 percent increments, the maximum allowed value is 0.957, or 110 percent of the minimal value. (At one point during the analysis, the base building transmittance was reduced to 30 percent of the minimal value, or 0.261.  After this change, the transmittance could be varied up to 200 percent without exceeding the 1.0 limit.)

The base building model had an rms error of 8.67 kBtu/hr over the 72-hour comparison period.  Figure 4.1 (Chapter 4) shows the base building simulated energy demand compared to the measured energy demand, as well as the measured inside air temperature.

**Roof insulation R-value.**  Results from varying all of the selected parameters of the base building model indicated that the minimum rms error for Run 1 was achieved with 30 percent of the minimal roof insulation R-value.  Figure 5.4 shows the variation of rms error with fraction of roof insulation.  As the insulation increases, the error increases and appears to level off at some maximum value.  Intuitively, this
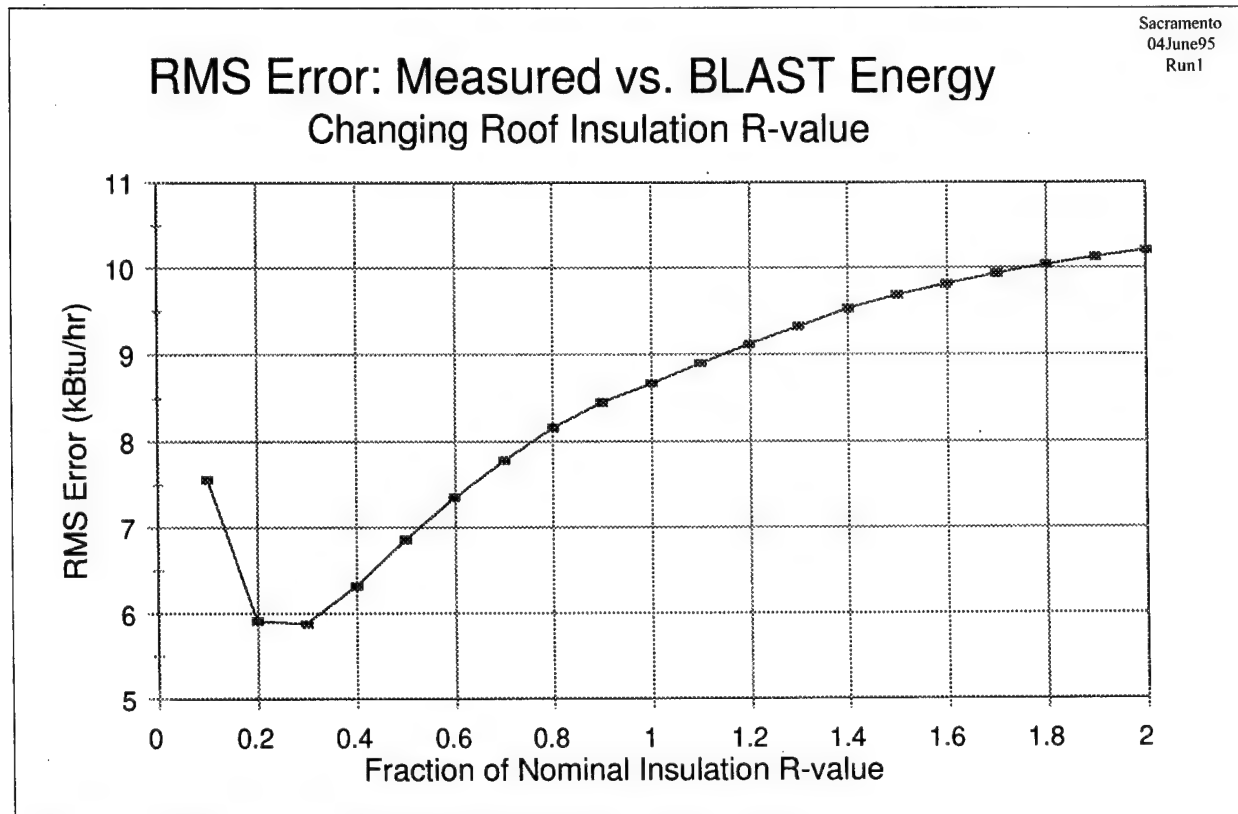
**Figure 5.4. Variation of rms error with changing roof insulation R-value.**

indicates that at some point the roof is so completely insulated that adding more insulation no longer affects the simulated energy demand of the model. As the insulation R-value approaches zero, the error would be expected to increase as if the building has only a plywood roof. A close-up of the behavior between the two extremes is shown in Figure 5.5. Changing this parameter to 30 percent of its minimal value reduced the rms error by almost 33 percent to 5.88 kBtu/hr.

Another parameter showing significant impact in reducing the rms error was the concrete thickness in the exterior wall. Changing the wall thickness to 10 percent of its minimal value reduced the rms error by about 22 percent to 6.77 kBtu/hr. Although the exterior wall thickness also influenced the simulated building energy performance, changing the roof insulation R-value clearly minimized the error for the first iteration of the analysis, Run 1.

Figure 5.6 shows the resulting simulated building energy demand compared to the measured values over the comparison period. The base building energy demand is shown by the triangles, and the results of Run 1 by the circles. Reducing the roof insulation by 30 percent appears to be a big change from the audit value. However,
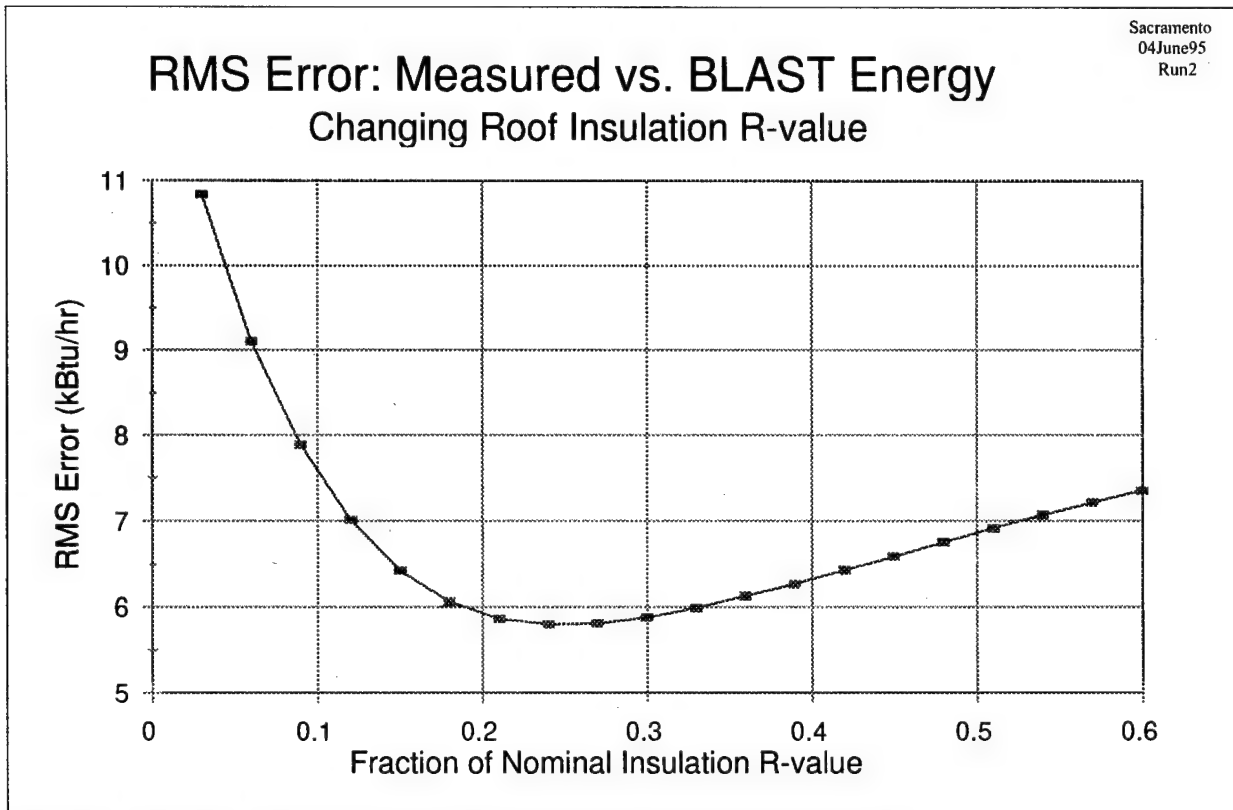
**Figure 5.5.  Close-up of Figure 5.4 showing rms error vs roof insulation R-value.**
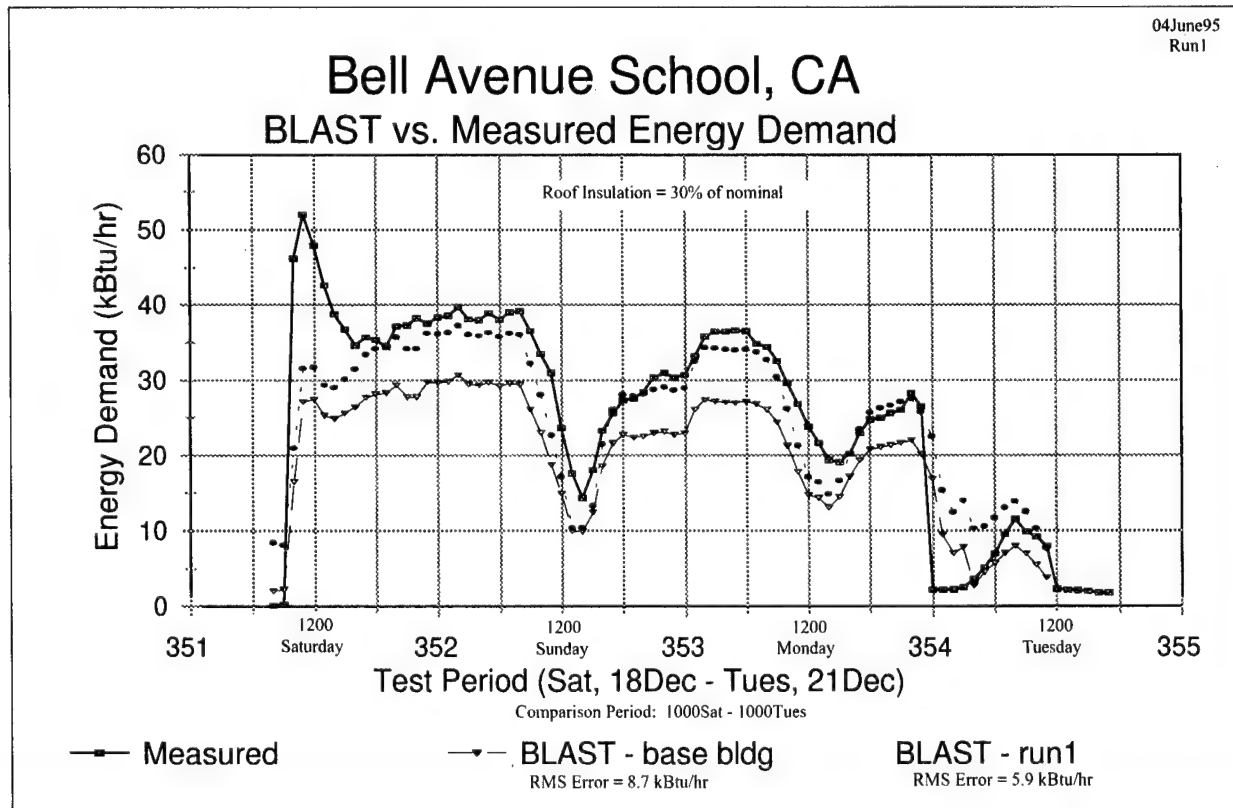


**Figure 5.6.  Simulated energy demand after reducing roof insulation R-value.**

because the initial roof insulation value was a guess and not based on actual building plans, this change may not be unreasonable.

As would be expected from decreasing the insulation in any building, the energy demand increases and shifts the whole simulated energy curve up. During various time spans, the change in energy demand is minimal, and at other times is more significant. The increases are especially large at night when the solar gains least influence the building's performance, and are smaller—even negligible—during the day. The magnitude of the roof insulation changed significantly, justifying the large shift in the simulated energy demand from the minimal case. Subsequent changes to the roof insulation during this analysis were not as large, resulting in more subtle changes to the energy demand curve. However, the trend, where the resulting energy demand is more strongly influenced at night and less strongly influenced during the day, is true through the whole analysis. Naturally, increasing the insulation decreases the overall energy demand, and decreasing the insulation increases the overall demand.

***Internal mass surface area.*** After changing the roof insulation to 30 percent of its minimal value, the second iteration began with the varying of the same parameters over the same ranges using the modified building model as the minimal input deck. From this run, it was found that increasing the internal mass surface area to 200 percent of its minimal value provided the greatest reduction in rms error. This reduced the rms error by about 12.5 percent to 5.15 kBtu/hr

Because parameters were only varied from 10 percent to 200 percent of minimal, changing the internal mass surface area to 200 percent of its minimal value was not necessarily a minimum of the curve. However, based on the procedure, it did provide the lowest rms error between the simulated and measured energy demands for Run 2. As a result, the surface area was doubled for the next iteration. Run 3 results also indicated that the surface area should be increased by 200 percent, or 400 percent of the base building value. The variation in rms error with internal mass surface area is shown in Figure 5.7, with fractional values ranging from 10 percent to 400 percent. From the curve, 200 percent of minimal is clearly not a minimum, but at 400 percent the rms error appears to be approaching a minimum. This second increase in the surface area reduced the rms error by 16.5 percent to 4.3 kBtu/hr.

Figure 5.8 shows how the simulated energy demand curve shifts when increasing the internal mass surface area from 100 percent to 400 percent. Run 1 results (30 percent of minimal roof insulation R-value) are shown by the triangles, and Run 3 results (30 percent of minimal roof insulation and 400 percent of minimal internal mass surface area) by the circles. By increasing the surface area, the simulated

# RMS Error: Measured vs. BLAST Energy
## Changing Internal Mass Surface Area
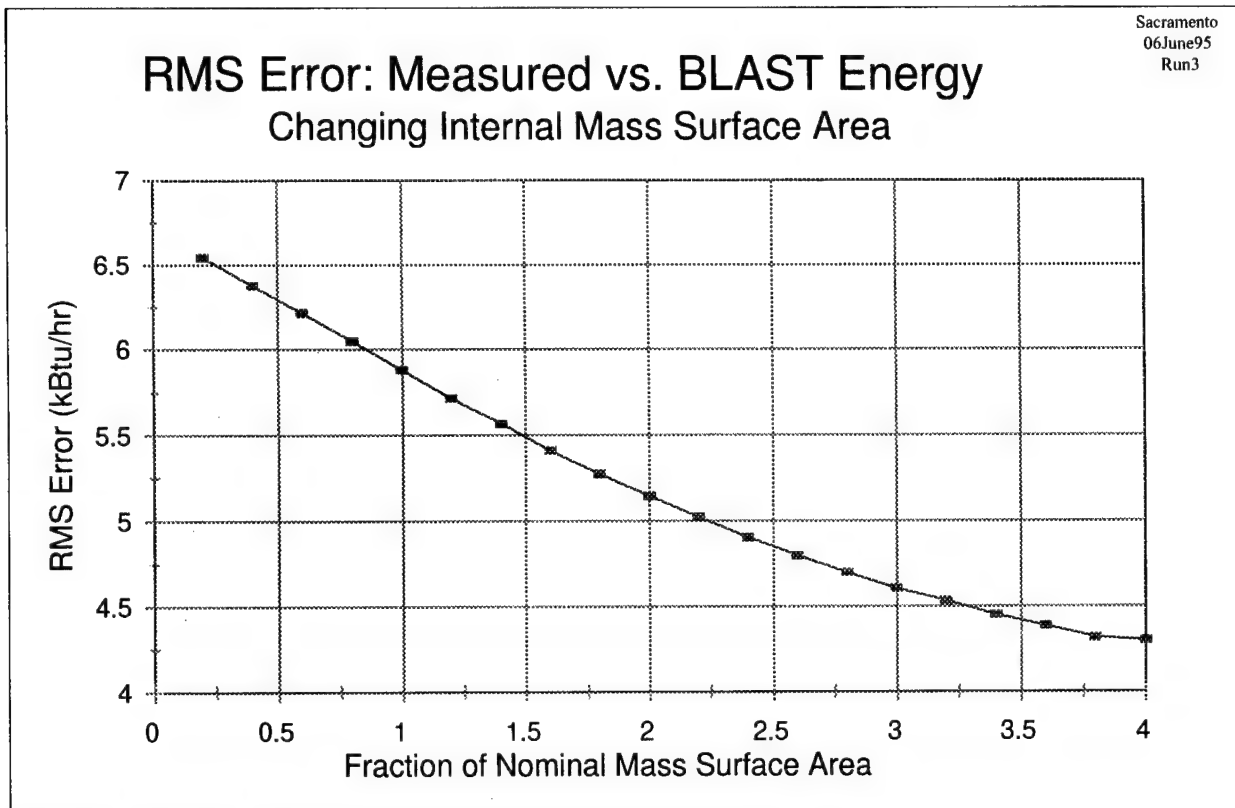


**Figure 5.7. Variation of rms error with changing internal mass surface area.**

# Bell Avenue School, CA
## BLAST vs. Measured Energy Demand



Roof Insulation = 30% of nominal
Internal Mass Surface Area = 400% of nominal

Comparison Period: 1000Sat - 1000Tues

| ■ Measured | ▼ BLAST - run1 | BLAST - run3 |
|---|---|---|
| | RMS Error = 5.9 kBtu/hr | RMS Error = 4.3 kBtu/hr |
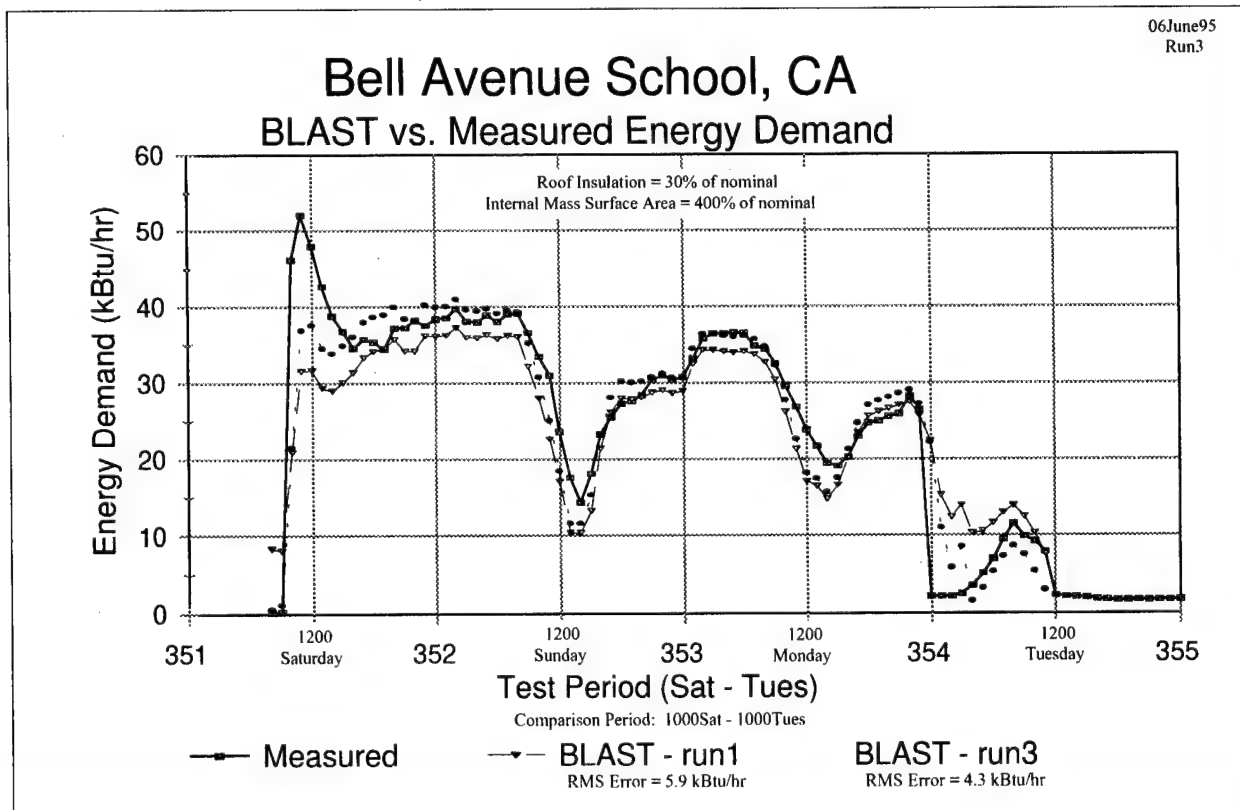
**Figure 5.8. Simulated energy demand after increasing internal mass surface area.**

building model appears to respond more rapidly to sharp temperature changes measured in the actual building. Referring back to Figure 4.1 in Chapter 4, two times are evident during the comparison period when the temperature changed rather sharply. At about 0900 Saturday the building was heated from about 58 °F to a constant temperature of 64 °F within 3 hours. Then at 2300 Monday, the space heaters and other internal gains were turned off for the cooldown test, allowing the temperature to drop from 64 °F to 59 °F.

During the Saturday warmup period, the simulated energy demand for Run 3 (circles) is lower than Run 1 (triangles) at the beginning and higher at the end of those three hours. The increased surface area appears to have stored enough energy during the previous hours to reduce the energy demand just before the warmup, matching the measured demand. At 0900 Saturday, the inside air temperature increased, as reflected by the sharply increasing energy demand. The building model, driven by the measured temperature profile, simulated an increased energy demand to charge the additional mass surface area and maintain the required inside air temperature.

On Monday, the power was turned off and the temperature dropped at a rate corresponding to the thermal properties of the building envelope. Increasing the internal mass surface area allowed the simulated building energy demand to respond to this more rapidly by increasing the amount of stored energy that could be quickly transferred to the space. During the cooldown, more stored energy was released from the additional surface area, decreasing the simulated demand required by the building.

During the constant temperature period, the simulated energy demand for Run 3 results was generally greater than for Run 1 results. This was observed more during the night, with only a minimal increase during the day. The day/night shift appeared to be a trend during the constant temperature period, but sharp temperature swings, when they occurred, dominated the response of the energy demand. Additional changes to the internal mass surface area later in the analysis revealed the same general trends, although the changes and results were not as drastic as those shown in Figure 5.8. The simulated energy demand responded most drastically to rapid temperature changes, showed a slight shift during the night and a minimal, if any, change during the day.

***Internal mass thickness.*** At this point in the analysis, three iterations had been performed resulting in one change to the roof insulation R-value and two changes to the internal mass surface area. Results from Run 1 dictated the change in roof insulation and Runs 2 and 3 determined the changes to the internal mass surface area.

From Figure 5.7 it was noted that the rms error appears to approach a minimum near 400 percent of minimal. As part of Run 4, the researchers varied the internal mass surface area in 10 percent increments near the modified value, and observed a minimum around 460 percent of minimal. However, Run 4 results indicated that the minimum rms error occurred by changing the internal mass thickness to 40 percent of its minimal value. This change reduced the rms error by about 6.6 percent to 4.03 kBtu/hr. The shape of the curve of rms error versus changing internal mass thickness was similar to that shown for the changing roof insulation value (Figure 5.4) and is not included here.

Figure 5.9 shows the simulated energy demand curves before and after decreasing the internal mass thickness to 40 percent of its minimal value. When changing the internal mass surface area, the amount of stored energy immediately available to the space changed. The building's response time to temperature changes decreased, allowing a sharper response in the energy demand curve to the changing temperature. Changing the internal mass thickness also influenced the energy storage capacity. In this case, however, the building responds to the different energy capacity over a longer or shorter time span, depending on the changing thickness. By decreasing the internal mass thickness, the energy storage capacity per square foot of internal mass area was reduced. This subsequently reduced the time required to charge and discharge the internal mass of the building.

From Figure 5.9, decreasing the internal mass thickness most significantly changes the simulated energy demand when the rapid temperature changes occur. Prior to the Saturday warmup, the demand was higher than for the previous run, and remained higher until around 1600 Saturday when the measured indoor temperature stabilized at 64 °F. This higher energy demand in the building with thinner internal mass indicated reduced thermal storage, increasing the demand for energy.

During the constant temperature period, the energy demand from Run 4 (thinner internal mass) appeared to remain slightly below that for Run 3 (minimal internal mass thickness), at some times more so than others. The thinner internal mass may have reached its thermal storage capacity, and energy entering the room is no longer charging the mass and maintaining the required temperature. Instead, the energy is used only to heat the room, reducing the total demand during that time. During the cooldown, from 2300 Monday to 0400 Tuesday, the thinner internal mass appeared to lose its stored energy at the same rate as the thicker mass, because the energy demand was about the same in the figure. Once the stored energy has been depleted, the simulated building energy demand for both building models increased again. However, the demand in Run 4 is greater than that in Run 3, possibly
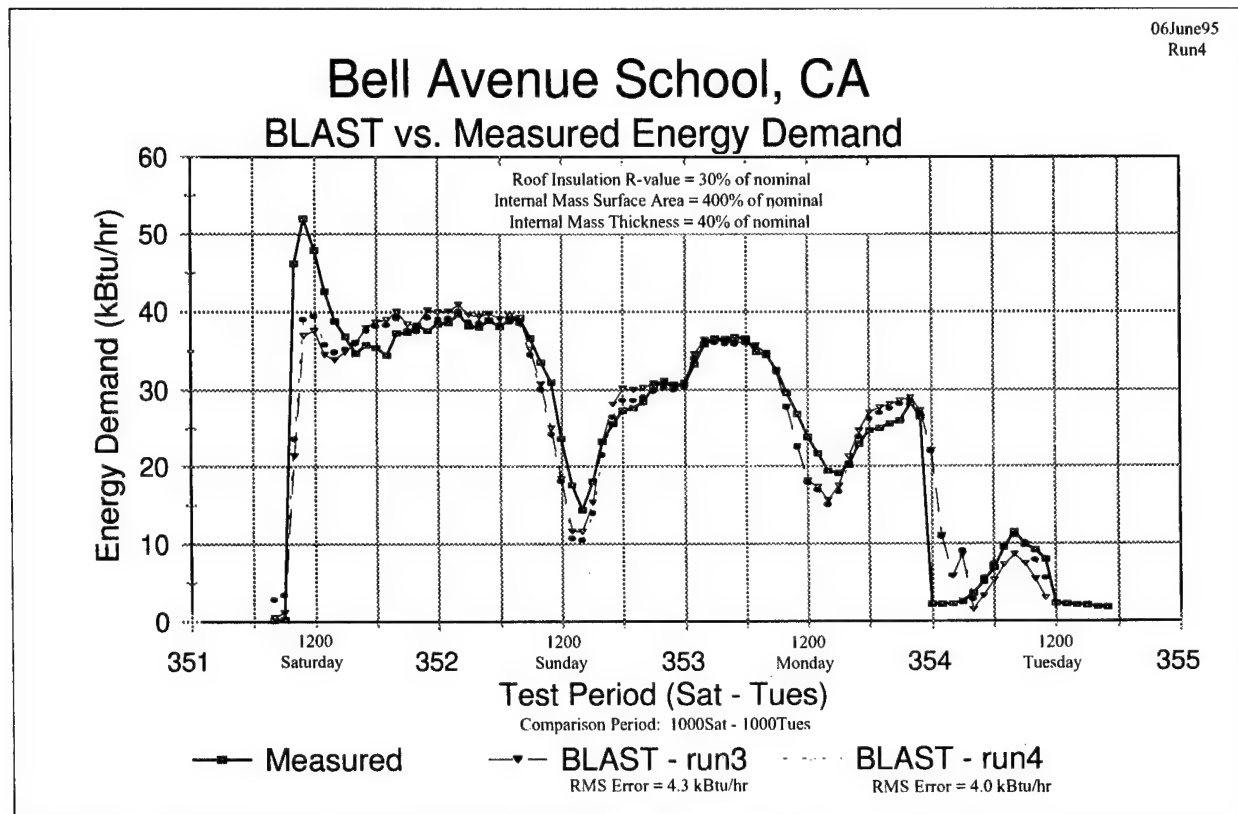
**Figure 5.9. Simulated energy demand after decreasing internal mass thickness.**

indicating that some of the demand for the building with the thicker internal mass is still being met by additional energy stored in the thicker mass.

Similar to other parameters, the internal mass thickness changed more than once during the analysis. After each modification to the thickness, the simulated energy demand curve shifted according to the same patterns noted above. During the warmup at the beginning of the comparison, the energy demand increased; during the constant temperature period the energy demand showed a minimal change; and during the latter part of the cooldown the energy demand again increased.

***Window transmittance.*** Another parameter modified during this analysis was the window transmittance. The rms error curve generated by changing the window transmittance was a simple parabola with a minimum around 30 percent of the minimal. Despite this significant decrease, the influence of changing the window transmittance on the building energy performance was minimal. Decreasing the transmittance reduced the rms error from 3.77 kBtu/hr to 3.66 kBtu/hr, only a 3 percent change. Figure 5.10 shows how the simulated energy demand changed after decreasing the window transmittance by 70 percent from the base building value.
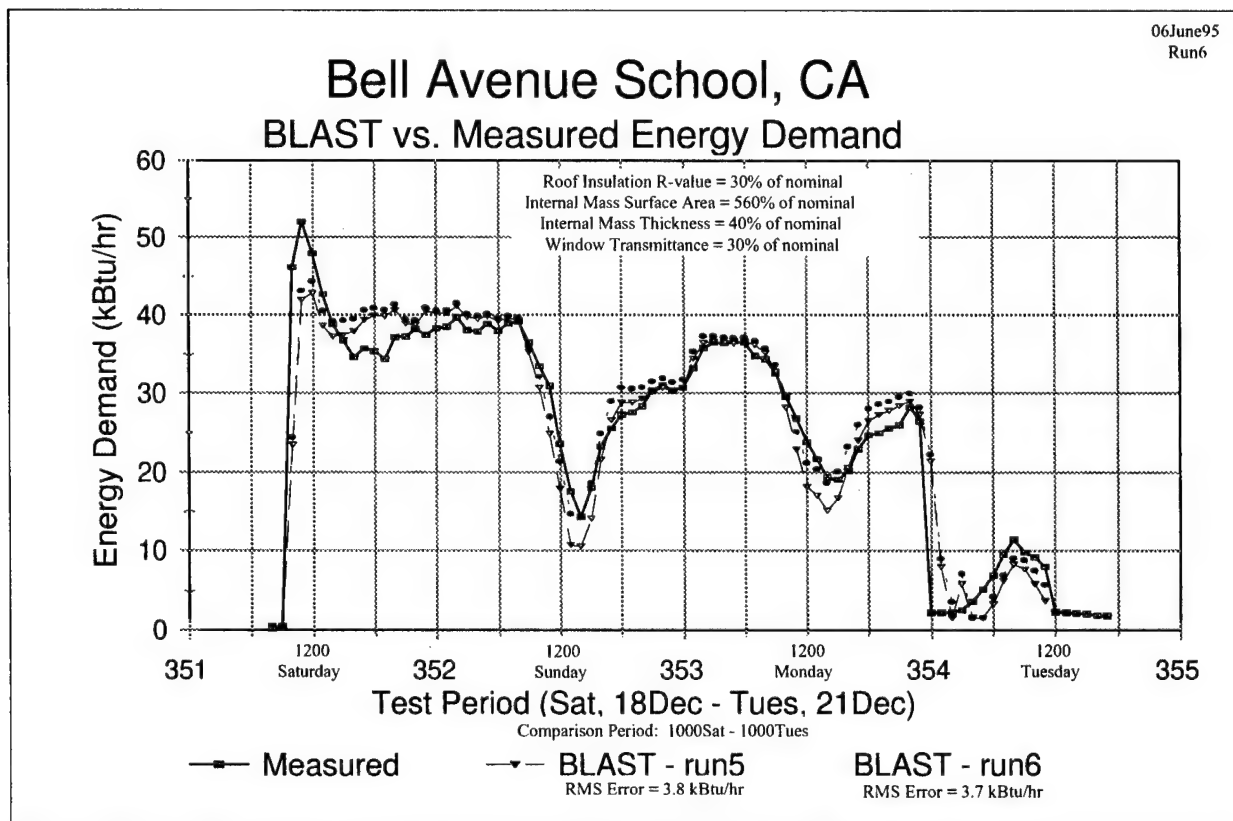
**Figure 5.10. Simulated energy demand after decreasing window transmittance.**

Because window transmittance influences a building's energy performance primarily in the form of solar gains, changes would mostly affect the energy demand curve during the daylight hours. Indeed, the hours most drastically influenced were between 1200 and 1700. However, changing the window transmittance appeared to influence the simulated energy demand curve over a wider range of hours from about 0900 to 2100. The rms error changed minimally at night. Decreasing the window transmittance generally increased the overall energy demand, noticeably increasing the simulated energy during the day on Sunday and Monday, with a less noticeable increase on Saturday and Tuesday.

**Results.** The building analysis progressed in steps similar to those described above. The process of finding the minimum rms error was repeated 14 times for the Bell Avenue School, the 14th run providing no significant decrease in the rms error as determined by the convergence criteria. Therefore, 13th changes were made to five parameters in the simulated building model, reducing the rms error from 8.67 kBtu/hr for the base building by almost 70 percent to 2.67 kBtu/hr. The iterations for the complete analysis are shown in Table 5.2

Table 5.2. Bell Avenue School analysis results.

**Bell Avenue School**
**Sacramento, California**

| Iteration | Parameter | percent of minimal value | 72-hour energy demand average 27.9 kBtu/hr RMS error (kBtu/hr) | 72-hour energy demand total 2009 kBtu R metric (kBtu) | percent decrease in RMS error from preceding run | percent decrease in RMS error from base building |
|---|---|---|---|---|---|---|
| Base Building | | | 8.67 | 491.25 | N/A | N/A |
| run1 | Roof Insulation R-value | 30.0% | 5.88 | 114.82 | 32.18 | 32.18 |
| run2 | Internal Mass Surface Area | 200.0% | 5.15 | 76.06 | 12.41 | 40.60 |
| run3 | Internal Mass Surface Area | 400.0% | 4.30 | 14.05 | 16.50 | 50.40 |
| run4 | Internal Mass Thickness | 40.0% | 4.03 | 32.04 | 6.28 | 53.52 |
| run5 | Internal Mass Surface Area | 560.0% | 3.77 | 10.95 | 6.45 | 56.52 |
| run6 | Window Transmittance | 30.0% | 3.66 | -86.01 | 2.92 | 57.79 |
| run7 | Roof Insulation R-value | 39.0% | 3.39 | 25.18 | 7.38 | 60.90 |
| run8 | Internal Mass Thickness | 24.0% | 3.14 | 34.14 | 7.32 | 63.76 |
| run9 | Exterior Wall Thickness | 70.0% | 3.01 | -35.92 | 4.14 | 65.26 |
| run10 | Internal Mass Surface Area | 616.0% | 2.95 | -37.53 | 2.09 | 65.99 |
| run11 | Roof Insulation R-value | 42.9% | 2.86 | -1.41 | 3.19 | 67.07 |
| run12 | Internal Mass Thickness | 14.4% | 2.80 | 2.76 | 2.00 | 67.73 |
| run13 | Internal Mass Surface Area | 739.2% | 2.67 | -11.19 | 4.72 | 69.25 |

Table 5.2 shows the parameter changed for each run, the percent of the change from the base building value, the resulting rms error, the R metric, and the incremental decrease in the rms error from the preceding run (used to determine convergence) and from the base building. The final rms error between the measured and simulated data is about 9 percent of the average hourly energy used during the 72-hour comparison period. The R metric was used to evaluate the difference between the total measured and simulated energy demands. The final difference is -11.19 kBtu, about 0.6 percent of the total 72-hour energy demand. The negative value indicates that the simulated building used about 11 kBtu more energy than the actual building during the comparison period.

The second-to-last column shows how the rms error changes from run to run, with a minimum decrease of 2 percent according to the convergence criteria. The last column shows how the rms error for each run decreases from the base building value, with a final error 69.3 percent less than the base building rms error.

A graph of the final simulated energy demand compared to the measured energy demand for the Sacramento building was shown previously in Figure 5.2.

*Discussion.* The final building model showed good agreement between simulated energy demand and measured building energy demand. Run 14 results (Table 5.3) show that all changes to any of the parameters in the most recent modified building model reduced the rms error by less than 2 percent. In fact, the minimum rms error for four of the parameters is at 100 percent of the parameter value from Run 13. The minimum rms error for the internal mass thickness (INTWALL - L) occurs at 90 percent of the value from the previous run, changing the error by only 0.34 percent. The minimum rms error for the transmittance (TESTGLASS - TRANS) was much less than the minimal parameter value, but the rms error decreased by less than 2 percent from the preceding run. Based on the convergence criteria, no further changes were warranted.

The parameters most impacting the simulated building energy performance were roof insulation R-value and internal mass properties. The base building energy demand was as much as 10 kBtu/hr less than the measured energy demand, and the rapid energy demand responses did not exist in the simulated building. Decreased roof insulation contributed to the necessary total increase in base building energy demand. Changing internal mass surface area and thickness provided the building properties necessary for a more accurate response to rapid changes in the indoor temperature.

Table 5.3. Results from Run 14—last run for Bell Avenue School based on convergence criteria.

| 11June95 | Sacramento fraction | TESTGLASS TRANS | fraction | ROOFINS R | fraction | DIMENSIONS INTMASS | fraction | EXTWALL L | fraction | EXTWALL K | fraction | INTWALL L |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| run 14 | 0.1 | 2.62 | 0.1 | 14.082 | 0.1 | 5.877 | 0.1 | 5.41 | 0.1 | 6.799 | 0.1 | 3.289 |
|  | 0.2 | 2.619 | 0.2 | 10.949 | 02 | 5.312 | 0.2 | 4.769 | 0.2 | 5.51 | 0.2 | 3.138 |
|  | 0.3 | 2.62 | 0.3 | 8.648 | 0.3 | 4.758 | 0.3 | 4.207 | 0.3 | 4.562 | 0.3 | 2.964 |
|  | 0.4 | 2.621 | 0.4 | 6.907 | 0.4 | 4.283 | 0.4 | 3.708 | 0.4 | 3.895 | 0.4 | 2.863 |
|  | 0.5 | 2.624 | 0.5 | 5.571 | 0.5 | 3.855 | 0.5 | 3.308 | 0.5 | 3.372 | 0.5 | 2.813 |
|  | 0.6 | 2.628 | 0.6 | 4.518 | 0.6 | 3.435 | 0.6 | 3.012 | 0.6 | 3.041 | 0.6 | 2.747 |
|  | 0.7 | 2.634 | 0.7 | 3.753 | 0.7 | 3.113 | 0.7 | 2.851 | 0.7 | 2.858 | 0.7 | 2.7 |
|  | 0.8 | 2.641 | 0.8 | 3.175 | 0.8 | 2.862 | 0.8 | 2.735 | 0.8 | 2.76 | 0.8 | 2.671 |
|  | 0.9 | 2.654 | 0.9 | 2.833 | 0.9 | 2.732 | 0.9 | 2.675 | 0.9 | 2.719 | 0.9 | 2.657 |
|  | 1 | 2.666 | 1 | 2.666 | 1 | 2.666 | 1 | 2.666 | 1 | 2.666 | 1 | 2.666 |
|  | 1.1 | 2.679 | 1.1 | 2.684 | 1.1 | 2.733 | 1.1 | 2.738 | 1.1 | 2.689 | 1.1 | 2.733 |
|  | 1.2 | 2.693 | 1.2 | 2.741 | 1.2 | 2.825 | 1.2 | 2.781 | 1.2 | 2.738 | 1.2 | 2.759 |
|  | 1.3 | 2.71 | 1.3 | 2.857 | 1.3 | 3.046 | 1.3 | 2.837 | 1.3 | 2.797 | 1.3 | 2.79 |
|  | 1.4 | 2.729 | 1.4 | 3.042 | 1.4 | 3.215 | 1.4 | 2.905 | 1.4 | 2.861 | 1.4 | 2.824 |
|  | 1.5 | 2.75 | 1.5 | 3.303 | 1.5 | 3.475 | 1.5 | 2.978 | 1.5 | 2.924 | 1.5 | 2.864 |
|  | 1.6 | 2.772 | 1.6 | 3.473 | 1.6 | 3.65 | 1.6 | 3.066 | 1.6 | 2.991 | 1.6 | 2.907 |
|  | 1.7 | 2.797 | 1.7 | 3.662 | 1.7 | 3.762 | 1.7 | 3.168 | 1.7 | 3.056 | 1.7 | 2.95 |
|  | 1.8 | 2.825 | 1.8 | 3.832 | 1.8 | 3.809 | 1.8 | 3.25 | 1.8 | 3.121 | 1.8 | 2.988 |
|  | 1.9 | 2.85 | 1.9 | 3.996 | 1.9 | 3.87 | 1.9 | 3.332 | 1.9 | 3.183 | 1.9 | 3.034 |
|  | 2 | 2.88 | 2 | 4.152 | 2 | 3.862 | 2 | 3.413 | 2 | 3.28 | 2 | 3.146 |
| minimum | ***** | ***** | ***** | ***** | ***** | ***** | ***** | ***** | ***** | ***** | ***** | ***** |
| RMS err | 20% | 2.619 | 100% | 2.666 | 100% | 2.666 | 100% | 2.666 | 100% | 2.666 | 90% | 2.657 |
| %smaller |  | 1.76 |  | 0.00 |  | 0.00 |  | 0.00 |  | 0.00 |  | 0.34 |

During the analysis, only primary parameters significantly impacted the model energy demand for any single run and were subsequently changed. During certain iterations, especially at the beginning of the analysis, the internal mass and exterior wall thermal conductivity reduced the rms error by more than two percent from the preceding run. However, these were never the most significant reductions. By the last iteration, the minimum rms error for both parameters was generated by 100 percent of their respective minimal values.

Various parameter minimal values were significantly increased or decreased, including the roof insulation, window transmittance, and internal mass surface area and thickness. As mentioned earlier in this section, the roof insulation changes may be attributed to a high estimate of the insulation R-value in the base building.

The significant decrease in window transmittance may be due to a combination of factors. First, after modeling the building based on sketches and information from the individuals who performed the STEM test, a discrepancy was found in window surface area. The building was modeled with about 820 sq ft of window surface area, but 690 sq ft were documented elsewhere. This 16 percent difference in surface area may partially account for the significant decrease in window transmittance during the analysis. Further analysis is required to verify the discrepancy. In general, however, the window transmittance was not one of the first or most significant parameters to be changed, and had a relatively low impact on the overall building energy demand.

Second, the building had a large amount of window surface area, almost 20 percent of the floor area, which may contribute significantly to the solar gains. However, the majority of solar radiation during the test period was diffuse because the sky was typically overcast. The solar gains during the test may account for some of the required decrease in window transmittance, but the decrease would be easier to justify with at least one day of clear sky and beam radiation to verify the results.

The internal mass properties changed in opposite directions. The surface area increased by more than seven times, and the thickness decreased to about one-seventh of the minimal value. The base building internal mass consisted of 8 in. thick, medium-weight concrete block with enough surface area to model the walls separating the four classrooms, about 1,590 sq ft. By increasing the surface area, the building's energy storage capacity is increased, and by decreasing the thickness, that capacity is decreased. However, as noted before, the two properties have different effects on the building's response time to temperature changes.

Prior to increasing the mass surface area in the building model, the internal mass thickness had a minimal effect on the simulated energy performance. After increasing the surface area by 400 percent, the next iteration revealed that the thickness should be reduced by 40 percent. The final internal mass properties can be attributed to the fact the actual internal mass is made up of more than just concrete block walls. The walls may be a portion of the internal mass, but text books, desks, tables, chairs and other miscellaneous items must also be included.

### 5.2.2    The Aspinall-Wilson Conference Center Simulation

The most difficult aspect in modeling the Aspinall-Wilson Conference Center was the variety of window orientations and unusual shapes. Not all of the windows from the actual building could be modeled with their exact orientation and tilt angle. However, the building model parameter variations should account for this discrepancy in achieving an accurate model.

From the base construction, four primary parameters (building insulation, window transmittance, internal mass surface area and thickness) and two others (internal mass thermal conductivity and the solar absorptivity of the interior brick surfaces and carpeting) were varied. The last two parameters were selected based on the strong influence that the windows were expected to have on the building energy performance.

The base building model energy demand compared to the measured demand is shown in Figure 5.11. The indoor air temperature, the top line, is also shown. The base building rms error was 22.65 kBtu/hr over the 54-hour comparison period from 1700 Friday through 2300 Sunday. Following the same approach used for the Sacramento building, all parameters were varied from 10 percent to 200 percent of their minimal values, except the window transmittance, which was initially varied from 10 percent to 110 percent of its minimal value.

For the Sacramento school building, the roof insulation was the parameter that most impacted the base building model. For the Gunnison building, this parameter was the window transmittance, which reduced the base building rms error by almost 57 percent from 22.65 kBtu/hr to 9.76 kBtu/hr. The rms error curve indicated an observed minimum at 30 percent of the minimal value. Figure 5.12 shows the simulated energy demand compared to the measured demand before and after changing the window transmittance.
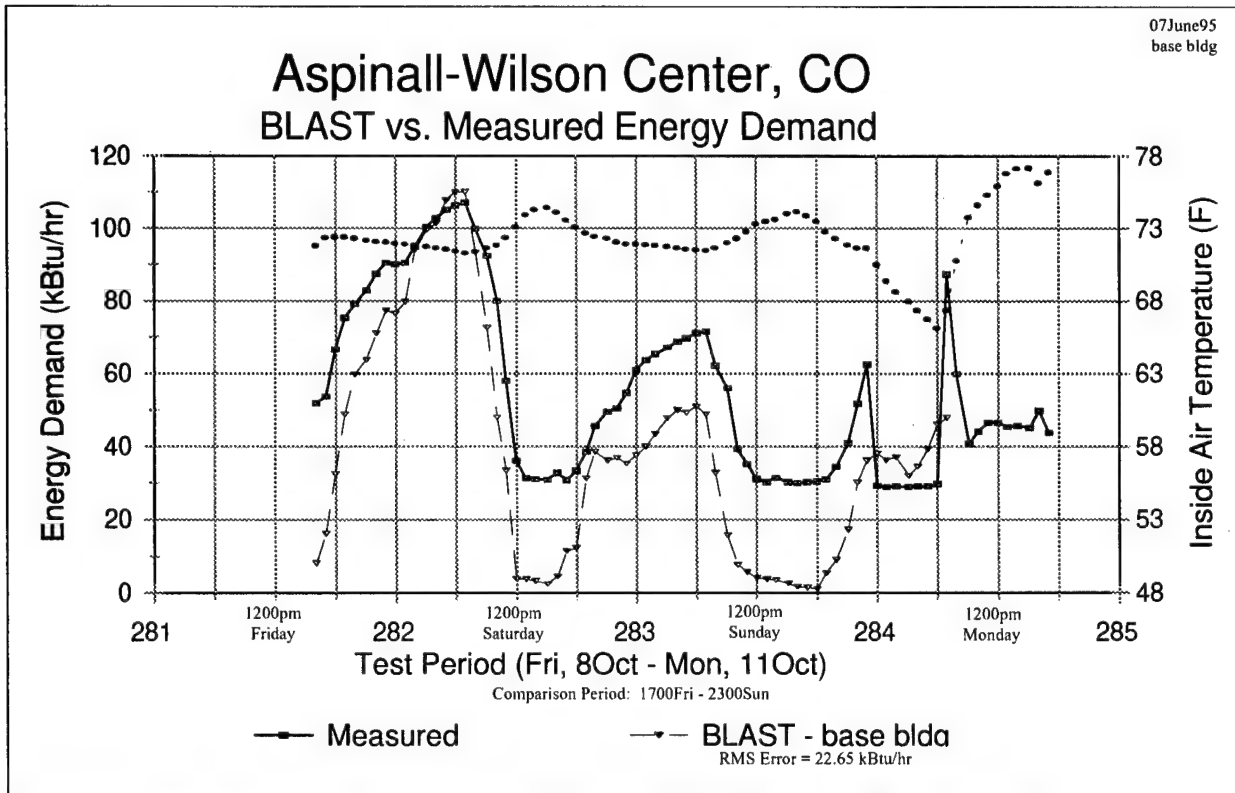
**Figure 5.11. Simulated vs measured energy demand for Aspinall-Wilson building base model.**
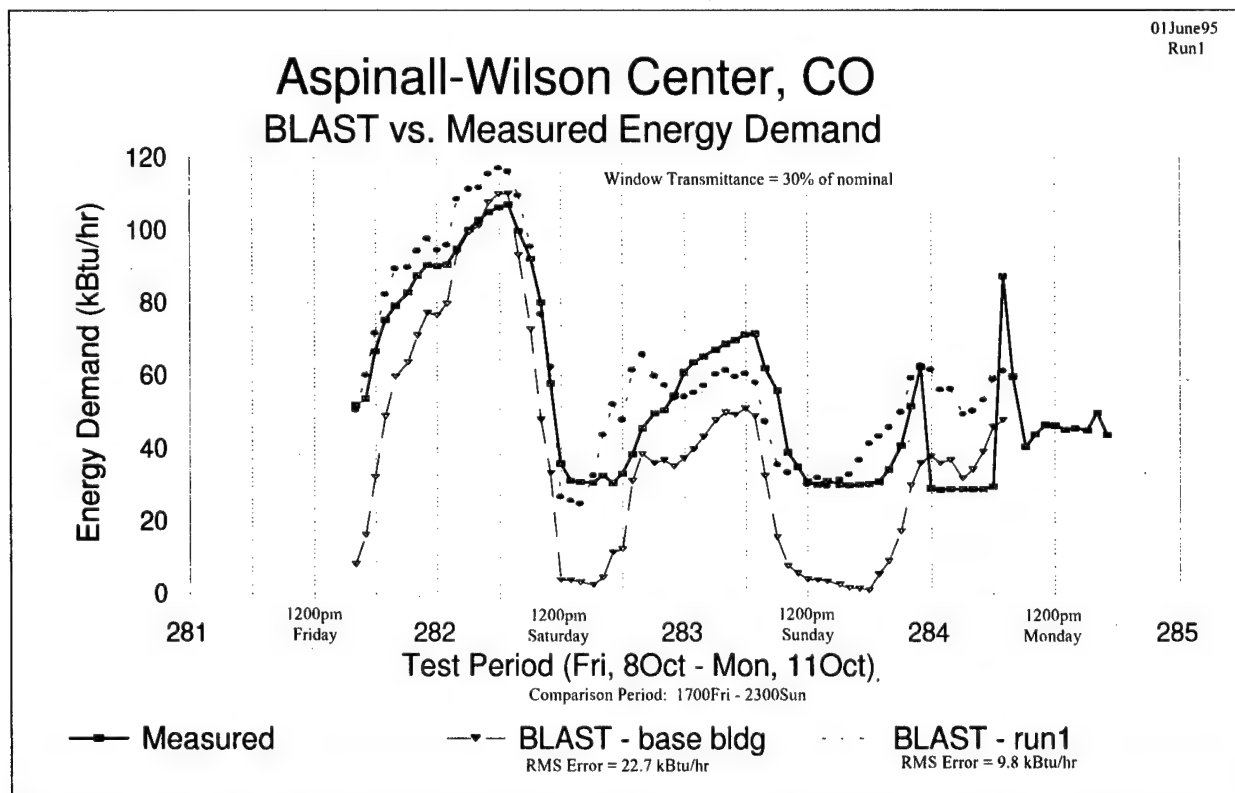


**Figure 5.12. Simulated energy demand for Aspinall-Wilson building after reducing window transmittance.**

Changing the window transmittance in the model clearly impacts the building energy performance differently during the night than during the day. This is most obvious in the figure from 1600 Friday to 1600 Saturday. The simulated energy demand shifts minimally from about 0200 Saturday through about 0700 Saturday and most significantly during the daytime hours from as early as 1000 through about 2200.

Subsequent changes to the building model did not impact the energy demand and the rms error quite as drastically as the window transmittance. In general, the rms error variations and parameter influence on the simulated building energy demand were similar to those presented above. The internal mass thickness and surface area, had rms error curve that was somewhat different than that for the Sacramento building. This is discussed below.

**Internal mass thickness.** When changing the thickness of the Gunnison building internal mass, the resulting variation of rms error is shown in Figure 5.13. The sharp drop in the curve from 60 percent to 70 percent of the minimal thickness did not appear in the curve for the Sacramento building.

Two major differences between the internal mass of the Sacramento building and that of the Gunnison building can begin to explain the different rms error curves.
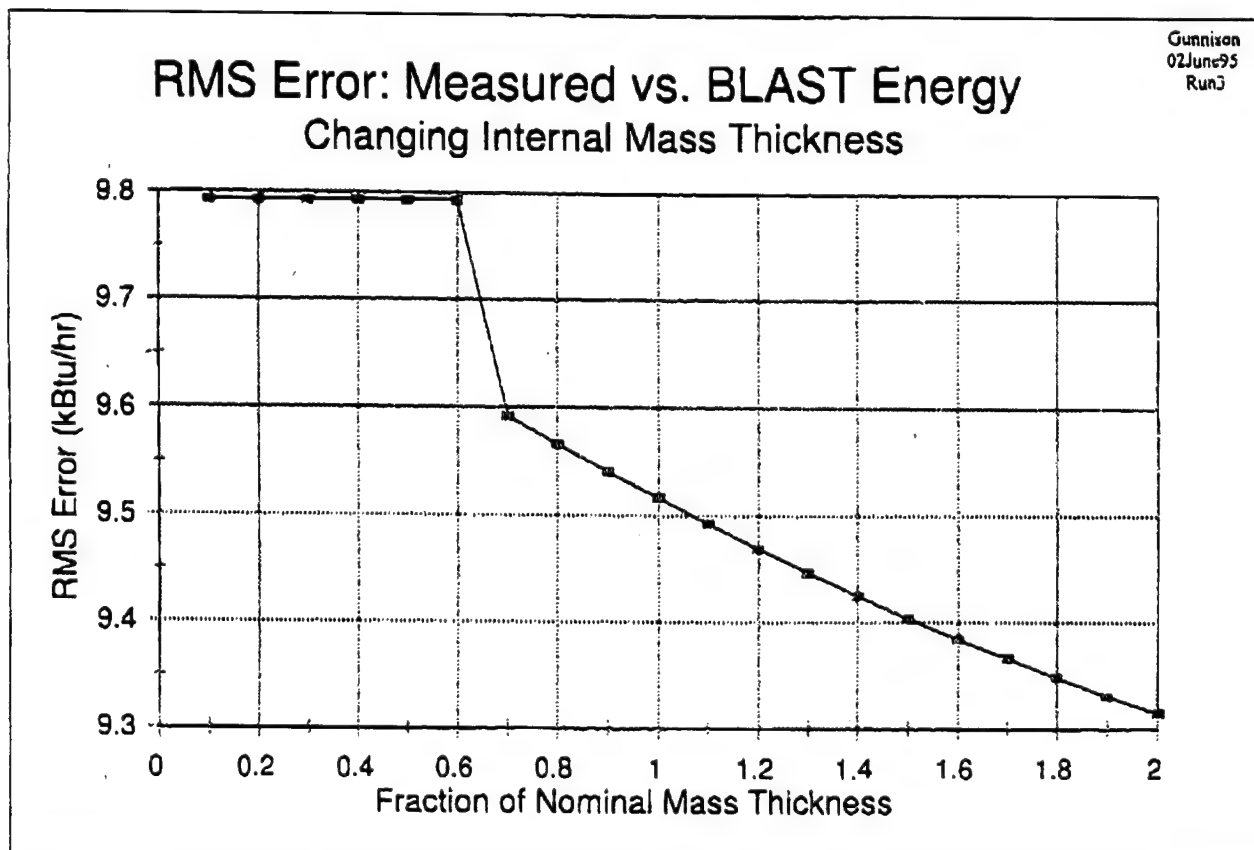


**Figure 5.13.** Variation of rms error for Aspinall-Wilson building with changing internal mass thickness.

First, different materials were used for the internal mass and second, the Sacramento base building mass thickness was almost thirteen times greater. The Sacramento internal mass consisted of 8 in. thick concrete block surrounded by two 5/8 in. thick gypsum board layers. For this building the internal mass thickness was changed by varying the concrete block thickness. The Gunnison building internal mass consisted of two similar gypsum board layers surrounding a vertical air space. In this case, because the gypsum board is the only mass layer, its thickness was changed during this analysis. The minimal gypsum board thickness was 5/8 in., giving the internal mass an effective thickness of 1-1/4 in. because there were two layers in the construction.

Below 60 percent of the minimal thickness (about 3/8 in.), the gypsum board may be too thin, and the building model no longer "sees" it. As a result, the simulated building energy performance is no longer influenced. At 70 percent and above, the internal mass is visible to the building and does influence the energy performance. This can be explained by looking at the response factors generated by BLAST for the gypsum board layer.

The response factors of a material indicate the energy flux at a surface of a wall in response to a temperature pulse at either that same surface or the other. The response factors are a function of the material properties, including the density, thermal conductivity and thickness. For a symmetrical wall the response factors are also symmetrical. Results from BLAST indicate that at 70 percent and greater of the minimal internal mass thickness, two response factors determined the energy flux on both sides of the mass. For minimal mass thickness of 60 percent and less, BLAST output showed only one response factor and no energy flux term, indicating no storage in the material. The thinner mass responded immediately to the temperature changes in the building as the mass were not there. The thicker mass stored some of the energy, delaying the response by at least one time step of the analysis. From this information, the researchers were able to clarify the results shown in Figure 5.13.

*Results.* The building analysis for the Gunnison building followed the same iteration procedure used for the Sacramento building. The convergence criteria were met after 10 iterations, resulting in nine changes made to the four primary parameters of the base building. The rms error was reduced from 22.67 kBtu/hr for the base building model by about 67 percent to 7.55 kBtu/hr. The complete analysis results are shown in Table 5.4.

**Table 5.4. Aspinall-Wilson Conference Center analysis results.**

| Aspinall-Wilson Conference Center Gunnison, Colorado | | | 54-hour energy demand | | | percent decrease in RMS error from | |
| --- | --- | --- | --- | --- | --- | --- | --- |
| | | | average | total | | | |
| | | | 60.0 kBtu/hr | 3242 kBtu | | | |
| Iteration | Parameter | percent of minimal value | RMS error (kBtu/hr) | R metric (kBtu) | | preceding run | base building |
| Base Building | | | 22.65 | 1093.38 | | N/A | N/A |
| run1 | Window Transmittance | 30.0% | 9.76 | -170.07 | | 56.91 | 56.91 |
| run2 | Roof Insulation R-value | 120.0% | 9.52 | -77.97 | | 2.46 | 57.97 |
| run3 | Internal Mass Thickness | 200.0% | 9.31 | -76.58 | | 2.21 | 58.90 |
| run4 | Internal Mass Surface Area | 200.0% | 9.06 | -94.04 | | 2.69 | 60.00 |
| run5 | Internal Mass Surface Area | 400.0% | 8.76 | -122.79 | | 3.31 | 61.32 |
| run6 | Window Transmittance | 36.0% | 8.4 | -29.50 | | 4.11 | 62.91 |
| run7 | Internal Mass Surface Area | 800.0% | 8.12 | -65.48 | | 3.33 | 64.15 |
| run8 | Window Transmittance | 43.2% | 7.84 | 57.94 | | 3.45 | 65.39 |
| run9 | Roof Insulation R-value | 96.0% | 7.55 | -59.32 | | 3.70 | 66.67 |

The final rms error between the measured and simulated data was about 12.7 percent of the average hourly energy used during the 54-hour comparison period. The R metric was used to evaluate the difference between the total measured and simulated energy demands. The final difference was -59.3 kBtu, about 1.8 percent of the total 54-hour energy demand. This indicated that the BLAST simulated building used about 60 kBtu more than the actual building during the comparison period.

The second-to-last column of Table 5.4 shows how the rms error changed from run to run. As for the Sacramento building, each incremental decrease was greater than 2 percent to meet the convergence criteria. The last column shows how the rms error decreased from the base building value for each run. The first iteration dropped the rms error by almost 57 percent, whereas the following eight iterations only reduced the error by an additional 10 percent.

A graph of the final simulated energy demand compared to the measured energy demand for the Aspinall-Wilson building is shown in Figure 5.14.

*Discussion.* The final Aspinall-Wilson building model showed good agreement between the simulated energy demand and the measured energy demand. Run 10
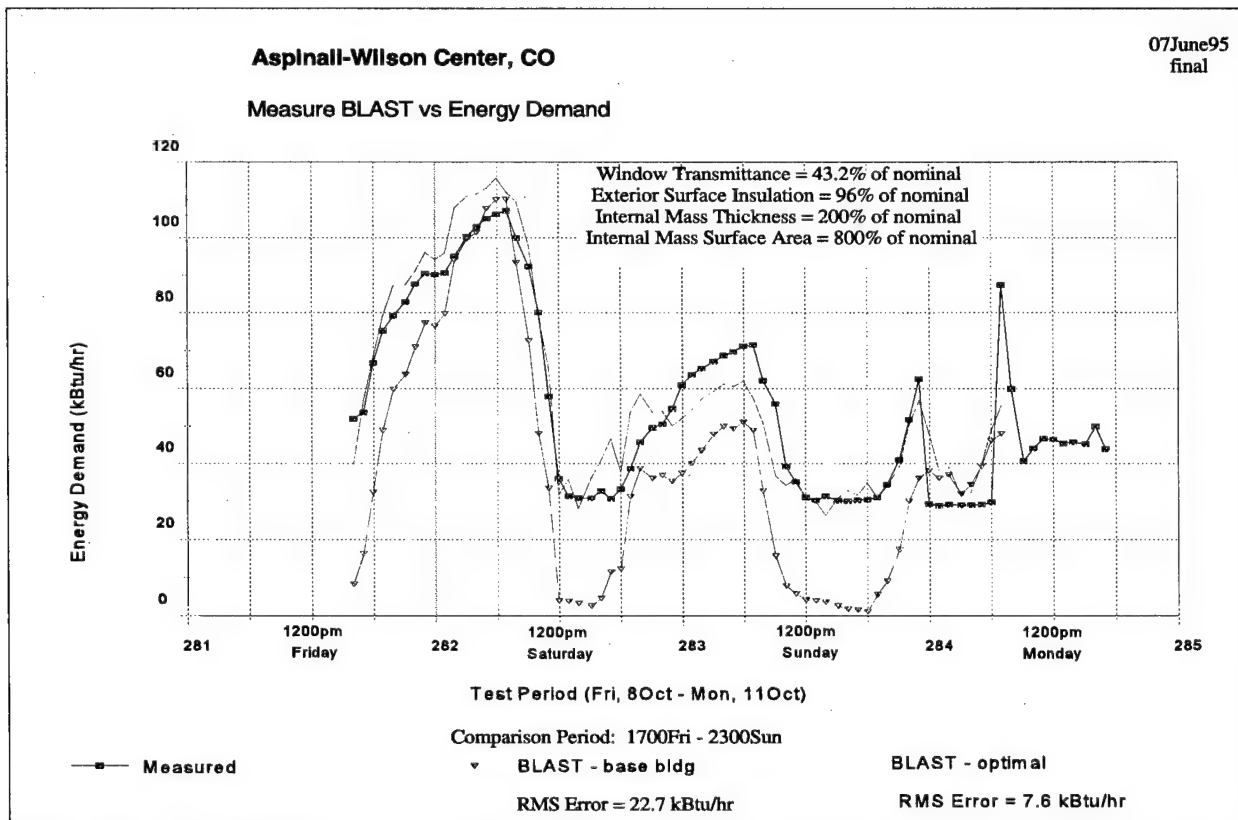


Figure 5.14. Final simulation results for Aspinall-Wilson building.

results showed that all changes to any of the parameters reduced the rms error by less than 2 percent. The majority of rms error curves from this run showed that the minimum error for each parameter was at 100 percent of its minimal value from the preceding run. The rms error for two parameters, the internal mass surface area and internal mass thermal conductivity, was not near 100 percent of the minimal parameter value. However, in both cases, changes to the error were less than the convergence criteria. The minimum rms error for the internal mass surface area was at about 140 percent of minimal, changing the error by only 1.6 percent. The minimum error for internal mass thermal conductivity was greater than 200 percent of the minimal value, changing the error by less than 0.4 percent. In fact, through the entire analysis, the internal mass thermal conductivity never changed the rms error by more than 0.4 percent.

The parameter most impacting the simulated building energy performance was window transmittance. The base building energy demand was significantly lower than the measured energy demand, especially during the day. Reducing the window transmittance in turn reduced the building model solar gains, increasing the overall energy demand from the simulated building systems. This shifted the energy demand curve up, most noticeably during the day.

The internal mass surface area was the parameter that changed most during analysis, increasing by eight times from the minimal value. From the base building BLAST deck, it was found that the original calculated internal mass surface area was about one-third short of the actual interior wall surface area. The additional surface area from the analysis results can be accounted for by books, chairs, desks and other objects typically occupying space in an office setting. The internal mass thickness also increased and appears to indicate that the building has more mass with a longer response time than originally modeled. This may be accounted for in the real building by additional brick surfaces not included in the base building model, including those of the fireplace and chimney.

The last primary parameter, the insulation R-value, initially increased to 120 percent of its minimal value, but later in the analysis decreased to 96 percent of minimal. In effect, the overall insulation value of the base building model was in good agreement with the insulation value of the actual building.

Only the four primary parameters had an impact on the building model for each run. The secondary parameters selected for this building, internal mass thermal conductivity and interior brick and carpet solar absorptivity, minimally influenced the building model energy demand. The absorptivity of the base building interior brick was 0.93, with a maximum allowable absorptivity of any material equal to unity.

Therefore, the researchers could only decrease the absorptivity in 0.1 fractional increments. This was done through Run 5, and the rms error only increased for decreasing absorptivity in all iterations. As a result, the minimum rms error was always at 100 percent of the minimal solar absorptivity. After Run 5, it was determined that changing the absorptivity had no positive influence in minimizing the rms error between the measured and simulated energy demands, and discontinued variations of this parameter.

### 5.2.3    The Building 7108 Simulation

The Fort Riley battalion building headquarters, Building 7108, was relatively simple to model based on the building plans and observations of the actual structure. The building is relatively massive, and was both the first and the second building tested using the STEM protocol. The winter test was performed in March 1993, and the summer test the following September. This is the only building with two sets of measured data for calibration, and the only building at this time for which summer test data were collected. The two sets of data provided the opportunity to verify building calibration for the winter test against the summer STEM test measurements.

From the base building construction, a total of ten parameters were varied. The four primary parameters included the window transmittance, the exterior insulation R-value, and the internal mass surface area and thickness. The other five parameters were varied to determine if changing the massive construction of the building impacted the simulated building energy performance. These parameters included the thermal conductivity and density of the internal mass, the thickness and thermal conductivity of the blocks on the inside of exterior walls, and the thickness of the exterior block construction. In the summer, the solar absorptivity of the roof was also varied. All parameters were varied from 10 percent to 200 percent of their minimal values, except for the window transmittance which was initially restricted to the range from 10 percent to 110 percent of minimal.

For this analysis, the building model was first calibrated using the winter measured data. The resulting modified building was then used to simulate the summer STEM test results. Based on the summer measured data, the winter building model required additional modifications to best fit the summer measured energy demand. The base building model was also calibrated using the summer test measurements, and the two results were compared.

The base building model energy demand compared to the measured energy demand for the winter test is shown in Figure 5.15. The average indoor measured tempera-
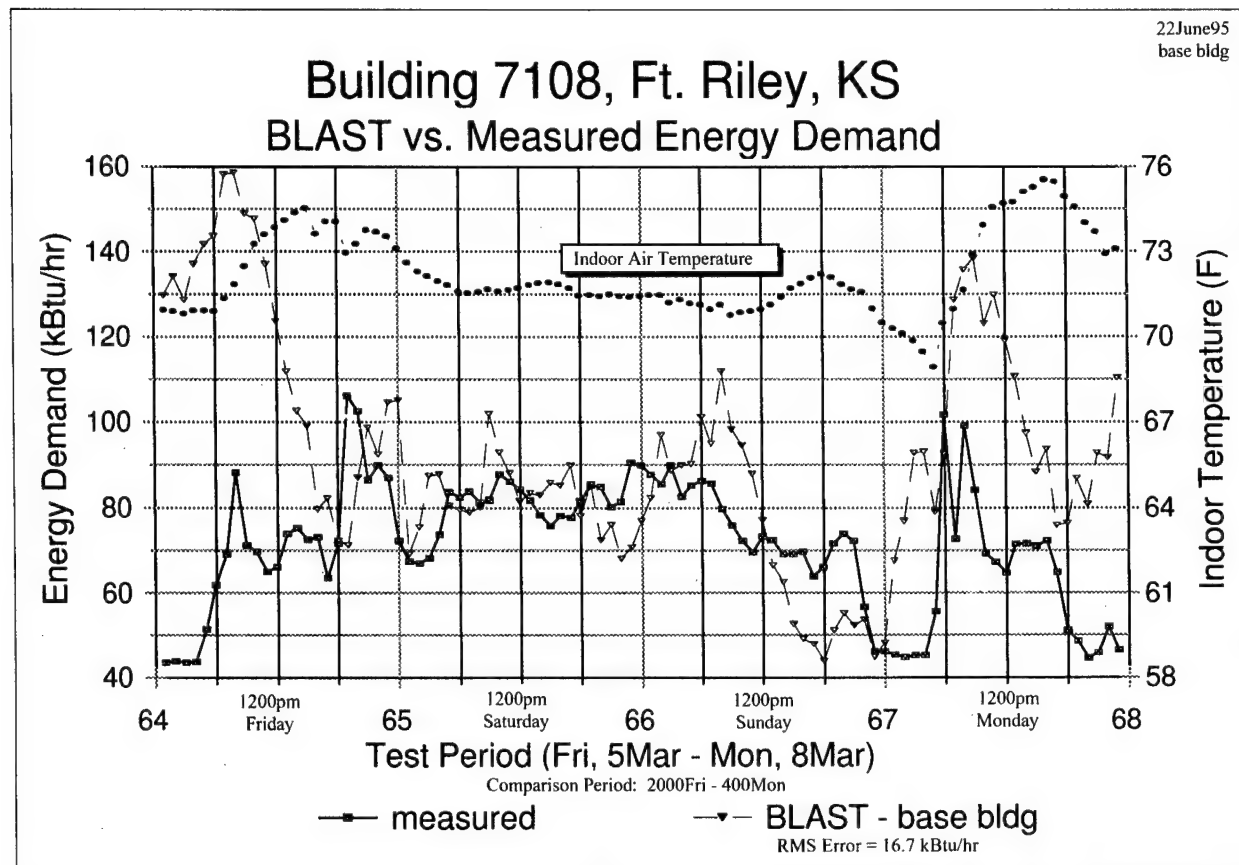
Figure 5.15. Winter simulated vs measured energy demand for Fort Riley base building model.

ture is also shown in this graph. The base building rms error was 16.68 kBtu/hr for the 57-hour comparison period from 2000 Friday through 0400 Monday. This starting error is about 22 percent of the average hourly measured energy demand. The indoor air temperature was held fairly constant at around 72 °F during the coheat period, with minimal increase due to solar gains. The cooldown period is also included in the comparison period. Neither the measured nor the simulated energy demand appear to remain steady through the coheating process.

Unlike the Bell Avenue School and Aspinall-Wilson buildings, no single parameter modification dramatically changed the rms error during the winter analysis. The first and only parameter that changed during this analysis was the internal mass surface area, which increased to 680 percent of the minimal value after three iterations. This is the first building in which the internal mass was specified using four different constructions, which were based on the building plans. The surface areas of all constructions were changed simultaneously. A fourth iteration showed the rms error would only change by 0.35 percent with further modifications to any of the parameters of the building model. The variation of rms error with the internal mass thickness was similar to that shown in section 5.2.1 for the Bell Avenue School.

To calibrate the Fort Riley building using the summer test results, two approaches were employed. In the first approach, the analysis was started with the same base building model used for the winter building calibration. In the second approach the base building model was used again, but the winter calibration results were used for Run 1 and the analysis started with Run 2. So in Run 1, the internal mass thickness was changed to 680 percent of the base building value.

Figure 5.16 shows the simulated cooling demand for both the base building and winter- calibrated building models compared to the measured summer cooling demand. The rms error between the simulated and measured energy demand for the base building model is 22.0 kBtu/hr over the 42-hour comparison period. The error drops to 18.9 kBtu/hr after the internal mass thickness was changed to 680 percent of the base building value, as dictated by the winter calibration results. The comparison period for the summer test was from 0000 Saturday through 1800 Sunday, which covered only the steady-state, coheat period.

In the summer, the temperature difference across the building shell was not large enough to justify changes to the building envelope. As a result, the researchers did
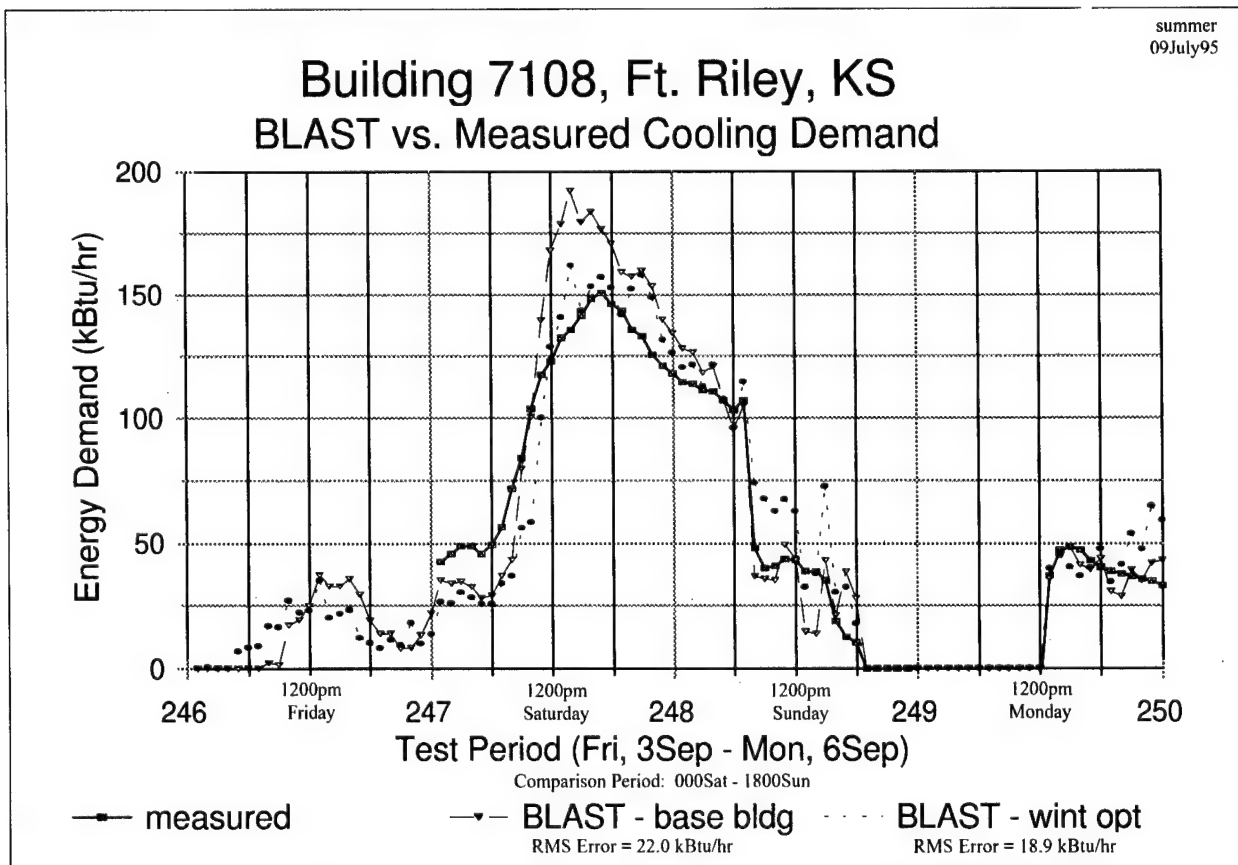


**Figure 5.16. Summer simulated vs measured energy demand for base and winter-calibrated Fort Riley building models.**

not change the exterior insulation R-value to calibrate the building using the summer STEM data. The results from several iterations, however, indicated that increasing the insulation R-value to 400 percent of the minimal value would have provided the greatest reduction in the rms error for that run. Instead, the solar absorptivity of the roof was modified with the intention of achieving a decrease in the building solar gain similar to that expected from increased building insulation. This parameter was not changed during the winter analysis because the weather during the test was primarily cloudy, with no significant direct solar radiation. During the summer test, however, the sun played a greater role in influencing the building energy performance.

In general, the rms error variations and parameter influence on the simulated building energy demand were similar to those presented for the Aspinall-Wilson building.

**Results.** The final results for the Fort Riley building calibration for the winter test were achieved after only three iterations, as noted above. The rms error was reduced from 16.7 kBtu/hr for the base building model by about 17.5 percent to 13.75 kBtu/hr. The complete analysis results for the winter calibration are shown in Table 5.5. The second-to-last column shows how the rms error changed form run to run, and the last column shows how the error decreased from the base building value for each run.

The final rms error between the measured and simulated data was about 18.2 percent of the average hourly energy demand during the 57-hour comparison period. The R metric indicates that the simulated building used about 22.3 kBtu more than the actual building during the comparison period. This is about 0.5 percent of the total measured energy demand during that time. The final simulated energy demand compared to the measured energy demand is shown in Figure 5.17.

Resulting rms errors and R metric values were similar for the two different approaches used to calibrate the Fort Riley building with the summer test data. The same parameters were modified in both cases, and followed the same increasing/decreasing trends.

The convergence criteria were met after seven iterations when starting strictly from the base building model, resulting in six changes to three building parameters. The rms error was reduced from 22.0 kBtu/hr for the base building model by about 27 percent to 16.0 kBtu/hr. The complete analysis results are shown in Table 5.6.

**Table 5.5. Building 7108 winter analysis results.**

Building 7108
Fort Riley, Kansas

| Iteration | Parameter | percent of minimal value | 57-hour energy demand | | | percent decrease in RMS error from | |
| --- | --- | --- | --- | --- | --- | --- | --- |
| | | | average 75.5 kBtu/hr | total 4304 kBtu | | preceding run | base building |
| | | | RMS error (kBtu/hr) | | R metric (kBtu) | | |
| Base Building | | | 16.677 | | -215.65 | N/A | N/A |
| run1 | Internal Mass Surface Area | 200.0% | 15.67 | | -186.66 | 6.038 | 6.038 |
| run2 | Internal Mass Surface Area | 400.0% | 14.239 | | -120.64 | 9.132 | 14.619 |
| run3 | Internal Mass Surface Area | 680.0% | 13.753 | | -22.31 | 3.413 | 17.533 |

Figure 5.17.  Final winter simulation results for Fort Riley building.

The final rms error between the measured and simulated data was about 18.6 percent of the average hourly energy used during the 42-hour comparison period. The R metric is 165.8 kBtu, about 4.6 percent of the total 42-hour energy demand.

The positive value indicated that the actual building used more energy over that time than the simulated building.  Figure 5.18 shows the final simulated energy demand for the first approach compared to the measured summer cooling demand for the Fort Riley building.

For the second approach using the summer data, the convergence criteria were met after five iterations, or four parameter changes to the base building model, including the changes indicated by the winter building calibration.   The complete analysis results for this approach are shown in Table 5.7.  The rms error was reduced 22.0 kBtu/hr by about 26 percent to 16.3 kBtu/hr, which is about 1.8 percent greater than the final error from the first approach.

The final rms error between the measured and simulated cooling demand was about 18.9 percent of hourly measured energy used during the comparison period.  The R metric is 137.4 kBtu, about 3.8 percent of the total 42-hour cooling demand.  Similar

**Table 5.6. Building 7108 summer analysis results—base building model.**

| Building 7108<br>Fort Riley, Kansas<br>from base building model | | | 42-hour energy demand | | | percent decrease in<br>RMS error from | |
|---|---|---|---|---|---|---|---|
| | | | average | total | | | |
| | | | 86.0 kBtu/hr | 3611 kBtu | | | |
| Iteration | Parameter | percent of<br>nominal value | RMS error<br>(kBtu/hr) | R metric<br>(kBtu) | | preceding run | base building |
| Base Building | | | 21.969 | -301.74 | | N/A | N/A |
| run1 | Window Transmittance | 20.0% | 20.091 | 75.45 | | 8.548 | 8.548 |
| run2 | Roof Surface Solar Absorpt. | 10.0% | 18.548 | 273.38 | | 7.680 | 15.572 |
| run3 | Internal Mass Surface Area | 200.0% | 17.578 | 329.9 | | 5.230 | 19.987 |
| run4 | Window Transmittance | 40.0% | 17.048 | 247.6 | | 3.015 | 22.400 |
| run5 | Internal Mass Surface Area | 300.0% | 16.479 | 293.59 | | 3.338 | 24.990 |
| run6 | Window Transmittance | 64.0% | 15.986 | 165.81 | | 2.992 | 27.234 |
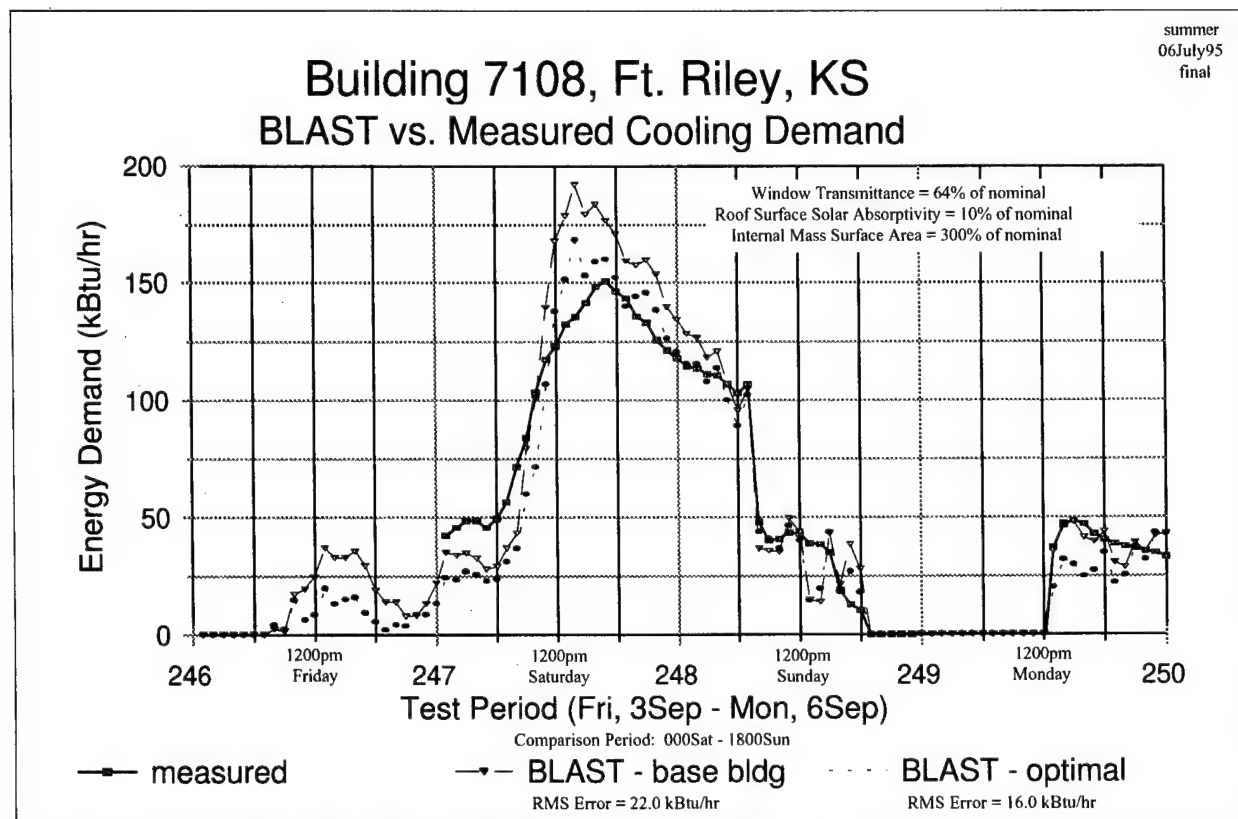
Figure 5.18.  Final summer simulation results for Fort Riley base building model.

to the first approach, the actual building uses more energy for cooling than the simulation model.  The calibrated building from the second approach uses about 17 percent less energy over that time than the other summer calibration.   Figure 5.19 shows the final simulated energy demand for the second approach compared to the measured summer cooling demand for the Fort Riley building.

*Discussion.*  In general, the winter rms error results are relatively good, and the R metric results, which indicate that the difference between the total measured and simulated energy is only 0.5 percent, tends to support the accuracy of the calibration. The poorer results for this analysis may be explained by the fact that the winter infiltration values used in the building simulation were not taken directly from tracer gas measurements, as they were for all the other tests.  Instead, continuous air-change-per-hour (ACH) values were derived using a regression model developed to characterize the data.  The final ACH values are based on the measured wind velocity (vw) and the outside-indoor temperature difference (dt) and given by the equation

$$a*vw+b*dt+c \hspace{4cm} \text{[Eq 3]}$$

where constants a, b, and c were fit to the data.

**Table 5.7. Building 7108 summer analysis results—winter calibrated model.**

Building 7108
Fort Riley, Kansas
using winter calibration results

| Iteration | Parameter | percent of minimal value | RMS error (kBtu/hr) | R metric (kBtu) | percent decrease in RMS error from | |
|---|---|---|---|---|---|---|
| | | | | | preceding run | base building |
| | | | 42-hour energy demand | | | |
| | | | average | total | | |
| | | | 86.0 kBtu/hr | 3611 kBtu | | |
| Base Building | | | 21.969 | -301.74 | N/A | N/A |
| winter opt | Internal Mass Surface Area | 680.0% | 18.864 | -87.99 | 14.134 | 14.134 |
| run2 | Window Transmittance | 70.0% | 18.071 | 109.46 | 4.204 | 17.743 |
| run3 | Internal Mass Surface Area | 476.0% | 17.287 | -11.18 | 4.338 | 21.312 |
| run4 | Roof Surface Solar Absorpt | 40.0% | 16.284 | 137.4 | 5.802 | 25.877 |
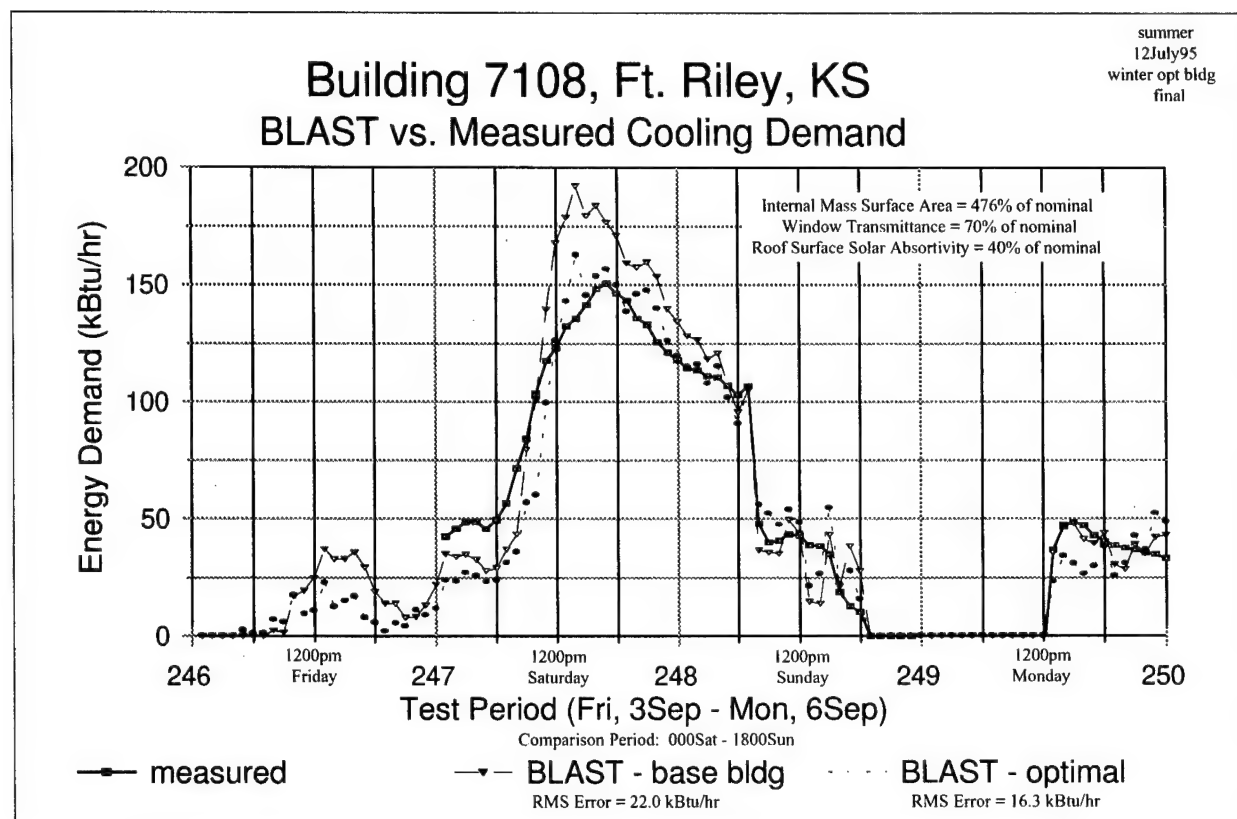
**Figure 5.19. Final summer simulation results for winter-calibrated Fort Riley building model.**

The two approaches used for the summer building calibration provided similar rms errors and R metric results. The rms error results were within 2 percent of each other, and the R metric results within 18 percent of each other. The same three parameters changed for both analyses, with the same general trends. The window transmittance decreased to 64 percent of minimal from the base building model, and to 70 percent from the winter calibrated building, a 6 percent difference between the two approaches. The roof surface solar absorptivity decreased to 10 percent of minimal from the base building model, and to 40 percent of minimal from the winter calibration building. The internal mass surface area increased to 300 percent of minimal from the base building model, and to 476 percent of minimal from the winter calibration building. The change in the solar absorptivity of the roof may not be as dramatic as it appears, because the value from the actual building is unknown and the value used in the BLAST input deck was an estimate.

The difference in the last two parameter final values for the two approaches is rather significant. One explanation may be that the two parameters interact in such a way that they compensate for each other, approaching an optimal value based on the other parameter value from the previous run. Also, during the analysis the researchers did not find the exact minimum rms error from a curve fit, but used the observed

fractional value. In section 5.1 the difference in results was noted when using the two different approaches on the same building. In general, the results are acceptable.

The final rms error for both summer and winter calibration results were from 18 percent to 19 percent of the average hourly energy demand during the respective comparison period. The R metric for the winter test was about 0.5 percent of the total measured energy demand during that time, which was consistent with the results found for the Bell Avenue School and Aspinall-Wilson buildings. The R metric for both summer analysis results was from 3.6 percent to 4.6 percent of the total measured energy during that comparison period, which is a reasonable result.

Unlike the Bell Avenue and Aspinall-Wilson buildings, no iteration reduced the rms error by more than 8.5 percent. This may indicate that no single parameter significantly influences the overall performance of the building. The Aspinall-Wilson base building model was strongly influenced by the window transmittance, and the Bell Avenue building strongly influenced by the roof insulation. The base building used for the Fort Riley calibration may have had a more correct simulation model from the beginning, as indicated by its lack of any one strongly influencing parameter.

### 5.2.4   The Director Building

As noted in Chapter 1 (section 1.3), the size and complexity of the Director Building prevented the researchers from applying the modeling and simulation techniques used on the other buildings. This building was included in the study mainly to determine whether a STEM protocol was logistically feasible for use on a large-scale office building. The results of the STEM field test for the Director Building are reported in section 3.4.3 (Chapter 3).

# 5  Summary, Conclusions, and Technology Transfer

## 6.1  Summary

Most current building commissioning procedures mainly address the administrative aspects of a building delivery cycle, i.e., verifying that various steps in the cycle have been addressed or completed.  Some of these procedures may include testing, but only on individual components.  However, buildings vary widely in size, layout, and function; the exact same HVAC hardware can perform very differently in two buildings of similar size and layout depending on construction materials, condition of the building envelope, orientation of the site, etc.  Consequently, conventional commissioning procedures are of limited value in ensuring good energy performance throughout a building's life cycle.  A building commissioning procedure that could adapt to these variables and provide reliable analysis would be of great value in both the government and private sectors.

This CPAR project has produced such a holistic proceure:  a technology-based energy-monitoring and analysis protocol for the performance commissioning of commercial-scale buildings.  The procedure—a STEM-based testing protocol—was used to collect energy-performance data from four buildings of various size, design, and locale (including one large, multistory office building).  These data were used with BLAST, in conjunction with BLASTED, PERL, and other supplementary software tools  to model each building's current construction, materials, energy systems, and retrofits. Each baseline model was compared with BLAST models created from each building's original design specifications.  A calibration system developed by the researchers was applied to identify and account for significant differences between design energy performance and actual energy performance.  The model-calibration process was generally capable of identifying the source of these differences and providing diagnostic data that could be used to improve the building's current energy performance.

In general, the simulated energy demand curves produced by the calibrated building models showed good agreement with the measured energy demand from each STEM test.  The rms error between the measured and simulated data generally ranged from 9.6 percent to 12.7 percent of the average hourly energy used during the

respective comparison period. In the case of the Fort Riley building results, however, the rms error reached 18.6 percent. The researchers attribute this data aberration to two causes:

1.  Fort Riley was the first building tested, so the results may indicate initial irregularities with the data-collection process
2.  Carbon dioxide was used at Fort Riley (but not in the later tests) as a tracer gas in measuring air exchanges, but because building occupants also generate carbon dioxide, some of the Fort Riley data may have been skewed.

The test periods ranged from 42 hours for the Fort Riley summer test to 72 hours for the Bell Avenue School test. Average hourly measured energy demand during the comparison period ranged from 27.9 kBtu/hr for the Sacramento building to 75.5 kBtu/hr for the Fort Riley building, or about 6.49 Btu/hr per square foot of the total floor area to 6.04 Btu/hr per square foot, respectively. The total energy demand of the calibrated building during the comparison was typically very close to that of the actual building, ranging from 0.5 percent to 4.6 percent of the total measured energy demand, with the majority of results less than 2.0 percent of the measured demand.

As indicated by the above results, the final simulated energy demand curves approximated the measured building energy demand during all phases of the test, including the steady-state coheat and cooldown periods.

The Bell Avenue School provided the best simulation results in terms of minimum rms error and R-metric values. This, however, was also the only building not influenced by occupants during any part of the test period. It was also the smallest building and had a very straightforward construction. Some of the parameters that were varied during the analysis changed significantly. However, because the base building model was created from observations rather than building plans, this was not surprising. Also, after considering the aspects of the building more closely, such as the significant furniture surface area not included in the original building model, the simulation results were found to reflect the actual building composition in both internal mass and exterior construction.

The Aspinall-Wilson Conference Center final building model also showed good agreement with the measured building energy performance. The most difficult aspect of the building to reconcile in the simulation model was the extensive glazing area and orientation. From the results, however, changing the window transmittance provided the desired effect on the building energy performance. The solar gains found in the measured energy demand curve are very similar to those found in the simulated building energy demand curve.

For both the Bell Avenue School and Aspinall-Wilson building, the first parameter changed in the analysis drastically reduced the rms error, significantly improving the fit of the simulated energy demand to the measured energy demand. The value for this parameter in the base building model may have been wrong, in which case the building model energy performance was extremely sensitive to initial variations of this parameter. From this, one can see how the actual building energy performance levels can be replicated by changing the physical parameters of a simulated building model. In the Fort Riley simulation, no single parameter variation for the base building model significantly improved the fit between simulated performance and actual energy use. In this case, the base building model may have been accurate enough, with differences between simulated and measured performance attributable to the data-collection problems noted above.

No simulation results were documented in this report for the Director Building because the facility was included in the research mainly to determine how well a STEM-based testing protocol would work on a large, multistory office building. Based on the findings discussed in Chapter 3 (section 3.4.3), the authors believe that there are no formidable logistical obstacles preventing the application of STEM to multistory office buildings such as the Director Building.

## 6.2  Conclusions

The monitoring protocol and supporting technologies were successfully demonstrated on four significantly different commercial and government buildings in different regions of the United States. The application of this protocol revealed defects in design, construction, or operations in each of the four buildings tested. For example, in one building air was entering rather than leaving through a relief damper. In another, economy-cycle operation of an air handling unit was prevented by a previously undiscovered control system design flaw. In a third, the test protocol revealed so much air infiltration that minimum building ventilation standards were being met even though the outdoor air dampers were taped shut for the winter.

From the buildings calibrated during this project, it is concluded that four primary building parameters may be expected to significantly influence the simulated building energy performance of building:

1.   building insulation
2.   window heat transmittance
3.   internal mass surface area
4.   internal mass thickness.

Not all of these parameters were changed during every analysis, but at least one, and typically more than two, were modified in the final building input file. In the case of the Aspinall-Wilson Conference Center, secondary parameters did influence simulated building energy demand, but not significantly in terms of the final results.

In general, the final results appear to indicate better agreement between the final simulated energy demand and measured energy use for smaller buildings. The trend also indicates that the buildings tested later in the program provided these better results.

It is concluded that the use of this new commissioning procedure and its supporting technologies can improve building energy performance, which can in turn produce better thermal comfort for occupants and lower energy consumption.

An original goal of this project was to develop a commissioning protocol that can be used by minimally skilled, but specifically trained technicians. However, the commissioning protocol developed here in fact requires a higher level of technical knowledge and expertise than envisioned. Untrained technicians—at least in the Corps of Engineers—will not be able to use this commissioning procedure without specific training and the intuition gained through field experience. This training requirement is not unique to the commissioning procedure documented here: the Corps has for some time been expected to use highly technical commissioning procedures that are intended to produce consistent-quality facilities. The training requirement for these procedures is considerable, but the intended facility quality is not being achieved. Training installation personnel to perform this CPAR-developed commissioning procedure could offer an excellent return on investment because the procedure has been shown to be capable of identifying systemic energy performance problems that elude existing commissioning techniques. The combination of technology-based performance monitoring, computer modeling, site-specific model calibration, and automated analysis offer great potential for improving facility energy-efficiency and occupant comfort.

Considering the potential benefits, it is concluded that training technicians to effectively apply this procedure would be reasonable investment toward a substantial facility management process improvement.

## 6.3   Technology Transfer and Commercialization

It is recommended that interested agencies and corporations consider establishing a team specifically tasked to carry out building commissioning. In the Army, such a team could be established at the District, Division, or Major Command level.

It is recommended that USACERL work with the Corps of Engineers, the Assistant Chief of Staff for Installation Management (ACS(IM)), the U.S. Army Center for Public Works (USACPW), and the other DoD services to identify more DoD buildings on which to demonstrate and validate the commissioning procedure.

Private-sector organizations that have an aggressive approach to building commissioning and a willingness to invest some resources in proactive operational improvements—utility companies and large property owners, for example—should be able to adopt this tool with relatively little delay. Because this is a recently completed project, however, the public awareness of this newly developed tool is limited. It is recommended that USACERL and Colorado State University jointly publicize this commissioning protocol through presentations at national conferences, including the Winter and Summer meetings of the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), the annual National Building Conference on Building Commissioning, and similar industry events.

# References

Amber, J.A., Leverenz, D.J., and Herron, D.L., *Automated Building Design Review Using BLAST*, Technical Report E-85/03/ADA151707 (U.S. Army Construction Engineering Research Laboratory, January 1985).

*BLAST 3.0 User's Manual* (University of Illinois, BLAST Support Office, 1990).

Schwartz, Randall L., *Learning PERL* (O'Reilly & Associates, Inc., 1993).

Solar Energy Laboratory, *TRNSYS 13.1 Manual: A Transient System Simulation Program* (University of Wisconsin-Madison, September 1990).

Subbarao, K., *PSTAR–Primary and Secondary Terms Analysis and Renormalization: A Unified Approach to Building Energy Simulations and Short-Term Testing*, TR-254-3175 (National Renewable Energy Laboratory, 1988).

# Appendix A: Building Model Calibration Procedure

Various components are necessary to complete a building calibration, including a base building model to simulate with the BLAST program, a BLAST formatted weather file, several DOS batch files, and PERL scripts. The following information details each aspect required for the analysis, and provides a step-by-step approach to the building calibration.

## A.1 BLAST Base Building Model

A base building model for simulation with the BLAST program can be created using several approaches. The user can create the entire base building input deck file using the BLAST user's manuals as guides for the proper input language and format. A BLAST preprocessor, BTEXT, can also be used to create the base building. BTEXT is an interactive program that prompts the user for building parameters and creates an input file with correct BLAST format and syntax. Both approaches require that the user create the entire BLAST input file. We found that the best method for creating an input deck with BTEXT is to use the preprocessor to create as much of the file as possible. This guarantees that the format is correct and readable. Once a *.bin file is generated, edit the *.bin file directly using an ASCII text editor. Because using BTEXT again will destroy the modified file, include as much information about the building as possible when creating the BLAST input deck. Although the preprocessor provides an easier method for creating a BLAST input deck, we recommend using BLASTED.

BLASTED is a program used to modify specially prepared BLAST input files. It is similar to BTEXT in that the proper syntax and format is handled by the program. However, when using BLASTED, the program starts with a building that has already been created in BLAST format. The user selects from five input files describing buildings of varying complexity, modifying only the desired parameters. The input files, called BLAST template files, include structures having a single story with one zone, five zones or nine zones, and a multistory structure with nine zones per floor or five zones per floor. BLASTED provides an easy way for users to change numbers

and text in the BLAST input file and gives users context-sensitive, on-line help. The user modifies various aspects of the given building, including but not limited to, the construction materials, wall and roof layers, building dimensions and window sizes. The user can also select from a complete list of fan systems and central plants and their specifications.

BLASTED is recommended because a base building input deck can be created quickly and with relative ease. In addition, the appropriate input file format and notation for building calibration using this method is imbedded in the BLASTED templates. A BLASTED User's Manual, with instructions for loading and running BLASTED, is also included in Appendix C of this report.

Using any approach indicated above, the base building is developed from the building plans (if available) to model the actual building as accurately as possible. Starting with a detailed simulation model of the building provides an advantage in that known building characteristics are included in the BLAST deck from the first run. Some of these known building characteristics include window size (area of the glazing surface), building wings and overhangs, internal mass construction, exterior wall and roof construction, and building orientation.

Buildings can be modeled using a single thermal zone or multiple zones. These BLAST thermal zones do not necessarily correspond to actual building office configuration or zones conditioned by any one system. For example, a rectangular office may be modeled with a single zone and lots of internal mass to account for the office partitions in the building. The structure may also be partitioned into five zones: four perimeter zones and one core zone. Any number of zone configurations can be used, but an objective for all models is to maintain relative simplicity in the model. The fewer the zones, the simpler the model. Further advice for partitioning buildings into zones can be found in the BLAST user's manual.

The following sections detail the necessary BLAST input deck components that allow the user to modify the base building, analyzing and optimizing its performance with respect to the actual building energy demand. As mentioned above, most of the format is imbedded in the BLASTED base building files and need not be initially entered by the user. However, when using BTEXT or creating a file from scratch, the user must specify each component in the base input deck using the format indicated. For all methods listed above, knowledge of the BLAST input language and file format is recommended. Various building details, such as overhangs and wings, require the user to modify the BLAST input file (the *.bin file) directly.

Examples of the BLAST input format are included in each section. However, the user should refer to the BLAST User's Manual for more complete information regarding the format and syntax of a BLAST input deck. The information listed below assumes that the user has access to both volumes of the BLAST user's manual.

### A.1.1    Lead Input

The following section explains the necessary Lead Input for a BLAST building file that will be used for building calibration. The majority of these components are incorporated into the BLASTED template files and need only be adjusted for the specific building. Input file details not already part of the BLASTED templates are indicated as such. When using BTEXT or an other approach to creating a BLAST input file, the following section should be carefully read and incorporated into the input deck. Along with the examples in each section, a complete BLAST input file has been included in Appendix B for reference.

*Temporary materials.* To allow changes in the base building model during the analysis, various building construction materials and their properties must be specified in the BLAST input deck. These include roof insulation R-value, exterior wall insulation R-value (where applicable), exterior wall construction material thickness (where applicable), internal mass construction material(s) thickness(es), and window glass transmittance. These account for the primary parameters typically varied in the base building model, except for the internal mass surface area. This parameter is specified in the Building Description section of the BLAST deck and is discussed later.

When defining a material, the user can describe it using its R-value (R) or the thickness (L), thermal conductivity (K), density (D) and specific heat (CP). As indicated above, insulation should be described using the R-value. Using R is appropriate for lightweight materials or for materials that are conductive compared to their total ability to store heat. The other four material properties should be used to describe materials with thermal storage capacity. By describing a material using its thickness, various secondary parameters, such as internal mass thermal conductivity or density, must also be used to describe the material. These parameters can often be used as secondary parameters to influence the building's energy performance. Only materials whose properties will be changed during the analysis must be defined as temporary materials. All others can typically be taken from the BLAST materials library.

Temporary materials can be described using the properties of materials included in the BLAST library, noting the library name for future reference. Special care should

be used when specifying the insulation R-value of walls and roofs. The actual wall insulation R-value is decreased by the parallel thermal conduction through the wood studs. For buildings with studs that are 16 in. on center, reducing the insulation R-value in the building model by about 66 percent or two-thirds provides a more realistic model of the actual building. If the insulation R-value from the building plans is used directly, recognize that an immediate drop in that primary parameter may occur, indicating a discrepancy between the building model and actual building.

The user must also be aware of and avoid using the same name for common materials used in different wall constructions. For buildings in which the exterior walls and interior partitions or internal mass walls consist of the same materials, specify two temporary materials with the same properties but different names. In this way, changing the internal mass thickness in the analysis only changes that parameter and not the thickness of the exterior walls as well. An example of the temporary materials used for a building analysis is shown below.

The user should note various aspects from the example below and include these in the BLAST input deck. The minimal value of each changing parameter should be indicated after the semicolon ending the material description. The two asterisks indicate a comment statement to BLAST, but putting the comment behind the end of the description precludes the comment value from being changed along with the desired parameter change. The material names should be fairly descriptive and include a comment indicating the BLAST material after which it was modeled, or some other reference. As with any computer code, comment statements and notations are at the discretion of the user, but are often useful for future reference. As mentioned above, we describe the insulation using the R-value, and the concrete block for the exterior wall and internal mass surfaces using the four material properties. The two concrete blocks have identical minimal properties but different material names, allowing changes to both the thickness and thermal conductivity of each block independently. The glass layer we define has the same properties as the glass used for double pane windows in the BLAST library.

```
TEMPORARY MATERIALS:
      ROOFINS        **IN2 - mineral fibrous, just R-10
          = (R=10.0,ABS=0.75,TABS=0.900,VERY ROUGH);    **minimal R=10.00
      EXTBLOCK       **CB57 - exterior wall
          = (L=0.667,K=0.2420,D=77.0,CP=0.200,ABS=0.20,
             TABS=0.900,MEDIUM ROUGH);    **minimal L=0.667
      INTBLOCK       **CB57 - interior wall/internal mass construction
          = (L=0.667,K=0.2420,D=77.0,CP=0.200,ABS=0.20,
             TABS=0.900,MEDIUM ROUGH);    **minimal L=0.667
      TESTGLASS      **GL1 - 1/8" clear sheet to model DPW
          = (R=0.024,ABS=0.75,TABS=0.900,TRANS=0.87,FILMTRANS=0.00,
             IR=1.52,VERY SMOOTH,GLASS);    **minimal TRANS=0.87
  END;
```

Other materials that have been selected as secondary parameters in the BLAST deck should also be included here. For example, users wishing to vary the solar absorptivity of the interior floor material must define a carpet or tile floor covering, specifying the solar absorptivity for that material.

*Temporary walls, roofs, floors, and windows.* The temporary materials listed above are used as layers in the building walls (exterior, interior, and internal mass), roof(s), floor(s), and windows. By changing the material properties, we indirectly change the characteristics of the building construction.

Temporary walls are used to describe exterior walls, interior partitions, interzone partitions and internal mass layers. When describing the layers of any temporary wall, the first layer listed is always the outside layer. For example, an exterior wall construction may be listed as 6 in. face brick, a building membrane, R-11 insulation, a vertical airspace, and 5/8 in. gypsum board. At least one of the temporary materials must be used to describe the exterior walls and the internal mass, although more than one is allowed. However, during the analysis, only one material and one property of that material should be varied at any one time for that wall construction. Interior partitions should be specified as internal mass using the material layers for interior partitions from the building plans. Interior mass walls are typically symmetric, requiring that only one temporary wall be defined.

Temporary roofs and floors include ceilings/floors between zones in a multistory building. Again, the first layer listed in the roof or floor construction is always the outside layer. For example, the roof description should start with the asphalt roofing or slate shingles and a slab floor description with a 12 in. dirt or gravel layer. See the BLAST manual for additional details on interzone ceilings and floors.

Temporary windows are specified similarly, but the listing of materials is irrelevant because the window is typically symmetrical. In the temporary materials, a temporary glass layer should have been specified using the desired glass properties from the BLAST materials library. Using this temporary glass, model a single-pane window by defining a window with a single layer of the glass. Clearly, a double-pane window has two glass layers with an air space in between, and a triple-pane window, three glass layers with two air spaces. When specifying the window size in the Building Description section of the input file, the window area should only include the actual glazing surface area, not any of the frame.

An example of temporary walls, roofs, floors and windows is shown below. Each construction has only one temporary material layer, using predefined materials from the BLAST materials library for the other layers. In this example, a temporary floor

was defined but no floor parameters were varied.  A floor from the BLAST floors library could have been used instead.  This is generally true, unless the user has determined that the floor may contribute significantly to the building energy performance and wishes to vary its parameters.  The temporary window is modeled after the double pane window defined in the BLAST library:

```
TEMPORARY WALLS:
     EXTWALL1
          = (CO27 ,        **stucco
               B1 ,        **airspace resistance, R=0.91
               EXTBLOCK ,
               B1 ,
               E8);        **5/8" gyp board
     EXTWALL2              **north wall, 12" deep cabinets built into wall
          = (CO27 ,        **stucco
               B1 ,
               EXTBLOCK ,
               B1 ,
               E8 ,
               B1 ,
               B1);
     INTWALL
          = (E6 ,   **½" sheathing board
               B1 ,
               INTBLOCK ,
               B1 ,
               E6);
END;
TEMPORARY ROOFS:
     TEMPROOF
          = (RF4 ,  **3/8" built-up roofing
               ROOFINS ,
               E8);
END;
TEMPORARY FLOORS:
     TEMPFLOOR
          = (DIRT 12 IN ,
               CO22 ,
               FF5);
END;
TEMPORARY WINDOWS:
     TEMPWINDOW
          = (TESTGLASS ,
               AR4 ,
               TESTGLASS);
END;
```

*Infiltration schedule.*  An infiltration schedule must also be specified in the Lead Input section of the BLAST deck.  During the STEM test, the building infiltration is measured and recorded in air changes per hour (ACH).  From this data, the user

creates a schedule similar to the example below. First, the maximum ACH value must be determined from the infiltration data. Using this value, the hourly fraction of the maximum infiltration is calculated by dividing the hourly data values by the maximum. These fractions are entered for each hour into the infiltration schedule, as seen in the example. Note that the measured data values for a specific hour include the data collected over the preceding hour and end at the time specified. For example, a 700 reading is for the hour from 600 to 700. Therefore, the hours indicated in the measured data file should correspond directly to those in the schedule.

```
TEMPORARY SCHEDULE (INFILT):
    THURSDAY = (0 to 24 - 0.40),
    FRIDAY = (0 to 1 - 0.43, 1 to 3 - 0.44, 3 to 5 - 0.41, 5 to 7 - 0.40, 7
             to 10 - 0.44, 10 to 11 - 0.47, 11 to 12 - 0.52, 12 to 13 -
             0.53, 13 to 14 - 0.58, 14 to 15 - 0.46, 15 to 16 - 0.43, 16 to
             18 - 0.40, 18 to 19 - 0.38, 19 to 20 - 0.40, 20 to 21 - 0.39,
             21 to 22 - 0.40, 22 to 23 - 0.39, 23 to 24 - 0.41),
    SATURDAY = (0 to 1 - 0.42, 1 to 2 - 0.41, 2 to 6 - 0.42, 6 to 7 - 0.41,
               7 to 9 - 0.42, 9 to 10 - 0.44, 10 to 17 - 0.42, 17 to 18 -
               0.41, 18 to 21 - 0.42, 21 to 23 - 0.43, 23 to 24 - 0.44),
    SUNDAY = (0 to 3 - 0.44, 3 to 5 - 0.45, 5 to 6 - 0.44, 6 to 7 - 0.45, 7
             to 8 - 0.43, 8 to 9 - 0.41, 9 to 10 - 0.43, 10 to 11 - 0.42,
             11 to 12 - 0.47, 12 to 13 - 0.49, 13 to 14 - 0.53, 14 to 15 -
             0.50, 15 to 16 - 0.41, 16 to 17 - 0.26, 17 to 18 - 0.22, 18 to
             19 - 0.20, 19 to 20 - 0.26, 20 to 21 - 0.15, 21 to 23 - 0.21,
             23 to 24 - 0.18),
    MONDAY = (0 to 1 - 0.20, 1 to 2 - 0.19, 2 to 5 - 0.17, 5 to 6 - 0.15, 6
             to 7 - 0.17, 7 to 9 - 0.16, 9 to 11 - 0.21, 11 to 12 - 1.00, 12
             to 13 - 0.37, 13 to 14 - 0.29, 14 to 15 - 0.23, 15 to 16 - 0.20,
             16 to 18 - 0.19, 18 to 19 - 0.20, 19 to 20 - 0.18, 20 to 21 -
             0.17, 21 to 23 - 0.19, 23 to 24 - 0.14),
    TUESDAY = (0 to 4 - 0.04, 4 to 5 - 0.20, 5 to 6 - 0.24, 6 to 7 - 0.33, 7
              to 8 - 0.31, 8 to 9 - 0.32, 9 to 24 - 0.40),
    WEDNESDAY = (0 to 24 - 0.40),
    HOLIDAY = MONDAY;
END;
```

The infiltration schedule is included in the Lead Input section of the BLAST file, but additional infiltration information must also be included in the BLAST Building Description. Refer to section A.1.2 of this appendix for details and an example of this input segment.

*Temporary controls.* The building calibration is based on modifying the base building model so that the simulated energy demand approximates the measured energy demand. To do this, we drive the building with the indoor temperatures measured during the STEM test. In some cases an average temperature is used to drive the entire building model. In others, a different temperature profile and schedule is used

for each zone based on an average measured zone temperature. This temperature information is specified using temporary control profiles.

The control profile allows the user to specify an indoor temperature that must be maintained during the building simulation. By doing this, we can collect simulation data showing the amount of energy required by the building model to maintain the indoor air conditions, and compare it to the actual building measured energy demand.

The temporary control includes two components, the profiles and the schedules. The profiles specify the conditions for which the zone needs heating, cooling or neither. The schedules specify the hours for which each profile is implemented. An example of a control profile using the measured temperatures from STEM data is given below. For multizone building models, several different temporary controls are typically necessary to model the different temperature profiles and scheduled of each zone.

```
TEMPORARY CONTROLS (MZ1):
     PROFILES:
          p57=(1.0 at 56.5, 0.0 at 57.5);
          p58=(1.0 at 57.5, 0.0 at 58.5);
          p59=(1.0 at 58.5, 0.0 at 59.5);
          p60=(1.0 at 59.5, 0.0 at 60.5);
          p61=(1.0 at 60.5, 0.0 at 61.5);
          p63=(1.0 at 62.5, 0.0 at 63.5);
          p64=(1.0 at 63.5, 0.0 at 64.5);
          p66=(1.0 at 65.5, 0.0 at 66.5);
          p67=(1.0 at 66.5, 0.0 at 67.5);
     SCHEDULES:
          FRIDAY=(0 to 1 - p61, 1 to 3 - p60, 3 to 11 - p59, 11 to 12 - p66, 12
to 15 - p67, 15 to 16 - p66, 16 to 17 - p64, 17 to 19 - p63, 19 to 20 - p66, 20
to 21 - p64, 21 to 22 - p63, 22 to 24 - p61),
          SATURDAY=(0 to 1 - p61, 1 to 3 - p60, 3 to 5 - p59, 5 to 7 - p58, 7 to
9 - p57, 9 to 10 - p60, 10 to 11 - p63, 11 to 24 - p64),
          SUNDAY=(0 to 24 - p64),
          MONDAY=(0 to 23 - p64, 23 to 24 - p63),
          TUESDAY=(0 to 1 - p61, 1 to 3 - p60, 3 to 11 - p59, 11 to 12 - p66, 12
to 15 - p67, 15 to 16 - p66, 16 to 17 - p64, 17 to 18 - p63, 8 to 19 - p61, 19
to 20 - p60, 20 to 22 - p59, 22 to 24 - 58),
          WEDNESDAY=(0 to 6 - p57, 6 to 11 - p59, 11 to 12 - p66, 12 to 15 - p67,
15 to 16 - p66, 16 to 17 - p64, 17 to 18 - p63, 18 to 19 - p61, 19 to 20 - p60,
20 to 22 - p59, 22 to 24 - p58),
          THURSDAY=TUESDAY,
          HOLIDAY=MONDAY;
END CONTROLS;
```

Before creating the temperature profiles and schedules for the building, the user must decide how many zones to model the building with, and the borders of each

zone. This information is necessary for calculating the average temperature of the whole building or averaging the indoor temperature measurements that correspond to a specific zone. Once the zones for the building model and corresponding average temperatures for each zone have been determined, the temperature profiles are created.

From the example, each temperature profile, denoted as p57, p58, p59, etc., covers a one degree Fahrenheit temperature range. The syntax "1.0 at 56.5, 0.0 at 57.5" indicates that, for that specific profile, full heating capacity is desired when the indoor air temperature is 56.5 °F and that the heating be turned off at 57.5 °F. During a cooling season test, similar syntax (0.0 at 56.5, -1.0 at 57.5) indicates that full cooling capacity is desired at 57.5 °F and that cooling be turned off at 56.5 °F. Because this STEM test was performed during the heating season, the profiles indicate that only heating is needed during this simulation. No cooling is specified in this profile or required during this test period.

Each temporary control is restricted to only nine temperature profiles, limiting the range of each profile and thus the degree of control of the simulated building temperature. For this test, the indoor temperature varied from about 56.5 °F to 67.5 °F which, when divided into one degree segments, requires eleven temperature profiles. From the example, however, only nine profiles are specified, indicating that two of the intermediate ranges were not measured during the comparison period.

Another option for describing the complete temperature range in the example above would have been to use 1.5 degree profiles. For example, a profile denoted by p75 would cover the temperature range from 74.25 °F through 75.75 °F. Using eight profiles defined in this way may have covered the entire range, but not demanded the same degree of simulated temperature control required by the narrower 1.0 degree profiles. For tests with a narrower overall temperature variation, 0.5 degree profiles may be an option. The smaller temperature ranges specified in the profiles allow more control over the indoor temperature of the simulated building model, providing more accurate building model energy demand.

To create the control profiles and schedule, the user must first determine the total temperature range of the measured data during the comparison period. From this the required number and range of profiles is found. The control schedule is created by using the correct profiles to specify the corresponding measured hourly temperatures. Temperature schedules must exist for each day simulated by BLAST. In some cases, complete data for days prior to and after the test is not available. Because these are typically days of normal operation, measured data from other normal days can be substituted into the blank spaces. Also, some temperature measurements

outside of the comparison period are not covered by one of the specified profiles. Using a profile that is specified and best models the measured temperature profile is adequate, because the measurement was not during the actual comparison period. By copying the measured temperature data from the original file to a separate file, a spreadsheet can greatly simplify this evaluation process.

*Weather tape and report file.* To use the weather file created using the weather data from the STEM test, the user needs to specify the dates of weather data using the following format. The specification should include accurate starting and ending dates of the weather file.

To generate the appropriate simulation data used for the analysis, a line in the BLAST input file must request the dates of the report file. This is also shown below. The weather tape and report file dates should be identical, and are typically included near the end of the Lead Input section in both BTEXT-generated and BLASTED input files. We also recommend including a comment statement that indicates the day of the week and Julian day corresponding to the dates. This is primarily helpful when verifying that all days and hours of the measured and simulated data are not shifted in time during the analysis.

```
WEATHER TAPE FROM 04MAR THRU 08MAR;
**    Thurs (JDAY=63) - Mon (JDAY=67)
REPORT FILE FROM 04MAR THRU 08MAR;
```

### A.1.2    Building Description

In the Building Description section, the physical aspects of the building are specified, including the location and orientation of each wall, the roof, the floor and the internal mass. Complete details of zoning a building and the BLAST input file format for correctly describing a building model should be taken from the BLAST user's manuals. Input to this section necessary for the building calibration process are specified here. The format for the required input is included in the BLASTED templates, and can be modified for the base building model. When using BTEXT, some of the details can be input using the preprocessor, but the user should verify that the appropriate format exists in the final *.bin file. For instance, the internal mass dimensions must be specifically entered by the user when BTEXT is used.

The following information must be included in the BLAST input deck to perform a building calibration: the internal mass dimensions, the zone infiltration and the zone controls.

*Internal mass dimensions.* The dimensions of various building parameters can be specified at the beginning of the Building Description section. In the BLASTED templates, this section is used to specify all building dimensions, including internal mass, wall and window heights and widths. For BTEXT users, this segment must be input directly into the *.bin file and need only specify the internal mass dimensions, as shown in the example below. Other building dimensions can be indicated directly for that construction. The format shown below is included in the input file before beginning the actual building description. The sample input file in Appendix B can be used for reference regarding the exact location of this input.

```
DIMENSIONS:
     INTMASSW1 = 150.0,
     INTMASSW2 = 130.0,
     INTMASSW3 = 120.0,
     INTMASSW4 = 335.0,
     INTMASSW5 = 78.0,
     INTMASSH = 9.0;          **minimal =9.0
```

The widths of the internal mass vary depending on the zone description, but a uniform height is assigned throughout the building. During the analysis, only a single parameter, the height, is varied.

When determining the internal mass surface area of a zone, a typical starting value is based on the total surface area of all partitions in that zone. For example, a thermal zone encompassing two offices separated by a partition would have an internal mass surface area that accounts for both sides of the partition. Do not include partitions that separate thermal zones, as these are indicated as interzone partitions. In general, we found that the internal mass surface area increased from 380 percent to 800 percent of the minimal value during the development of this process. Tripling the base value determined above for office spaces may more accurately model all surfaces in a typical office environment, such as desks, chairs, tables, books, bookcases and other furniture and surfaces. For thermal zones with more open space and minimal office-type areas, doubling this value may be more accurate. In all cases, starting with the value that includes only the interior partitions surface area is appropriate. The internal mass surface area may significantly change during the analysis, which can be anticipated.

After specifying the dimensions as indicated above, the internal mass wall type and surface area must be described for each zone. The format, identical for every zone, is shown below. INTWALL refers to the internal mass construction defined as a temporary wall. In general, the internal mass construction must not be defined as

a temporary wall, because only the dimensions are being changed. However, if other properties of the internal mass, such as the thickness or thermal conductivity, may influence the building energy performance, the mass must be defined as a temporary wall by the user. The width in the example is specified using the dimension equivalent to INTMASSW1, but can be input numerically as well, because its value is not changed during the analysis. The internal mass height, however, must be specified using INTMASSH in order to vary the internal mass surface area during the building calibration.

```
      INTERNAL MASS:
           INTWALL (INTMASSW1 BY INTMASSH);
or
      INTERNAL MASS:
           INTWALL1 (150 BY INTMASSH),
           INTWALL2 (230 BY INTMASSH1);
```

More than one internal mass construction can be specified for a zone. For example, one partition may consist of concrete blocks, while another of drywall. Each internal mass construction can be changed individually to determine which may have the most significant influence on the simulated energy demand, or all constructions can be changed simultaneously. When varying each construction separately, the internal mass height must be identified using different variables in the dimensions.

In our experience, the impact of changing each internal mass surface area separately reduces the overall influence of the total parameter on the building energy performance. Each individual mass may not influence the building enough to warrant a change, minimizing the fact that the total internal mass surface area does indeed influence the simulated energy demand. We recommend changing the surface area of all internal mass constructions simultaneously.

*Zone infiltration.* In the Building Description, each zone is assigned a peak infiltration level and an infiltration schedule, namely the temporary schedule defined in the Lead Input. The peak infiltration level, in cubic feet per minute (cfm), must be calculated for each zone, based on the total building volume and the zone volume. First the maximum ACH value determined above is converted to cfm by multiplying this value by the total building volume (in cubic feet) and dividing by 60 (to convert from hours to minutes). For a building modeled with a single zone, this is the only calculation and the resulting cfm value is the peak infiltration level. For buildings with two or more zones, the fraction of the total volume occupied by each zone in the building is calculated. These same fractions are applied to the total maximum infiltration value, and each zone assigned its peak infiltration based on these

calculations. In this way, the total building infiltration is distributed evenly throughout the building. An example for specifying the infiltration is shown below.

```
INFILTRATION = 398.8, INFILT,
    WITH COEFFICIENTS (1.0, 0.0, 0.0, 0.0),
    FROM 01JAN THRU 31DEC;
```

The infiltration in this example peaks at 398.8 cfm, and fluctuates according to the predefined infiltration schedule. The days indicated in the example, FROM 01JAN THRU 31DEC, should include the simulation period. We could have also specified the same time period covered by the weather file and report file, but because the simulation covers only those times and no more, this is not necessary in this case.

*Zone controls.* The zone controls invoke the temporary control profiles and schedules for that zone, dictating the zone load required to maintain the measured temperature profiles. The BLAST input format is shown below.

```
CONTROLS=MZ1,
    21.33 HEATING, 0.0 COOLING, 0.00 PERCENT MRT,
    FROM 04MAR THRU 08MAR;
```

MZ1 is the name of the temporary control defined in the Lead Input. The heating capacity for each zone is determined following the same procedure used to calculate the peak infiltration per zone. First, the maximum measured energy demand (kBtu/hr) is determined from the data. Then, using the fraction of the total volume occupied by each thermal zone, the fraction of the maximum energy demand for each zone is calculated. This distributes the total energy demand through the building based on each zone volume. From the example, this zone has 21.33 kBtu/hr of available heating capacity. Because the test was performed during the heating season, no cooling capacity is required or provided. For all zones and in all cases, the PERCENT MRT is set to zero. Similar to the infiltration schedule, the dates indicated here could have covered the entire year or, as in the example, just the simulation period.

### A.1.3   Fan Systems

The building fan systems are specified in this section of the BLAST input deck. The parameters of the actual building system should be input as accurately as possible, including cold and hot deck temperatures, supply air volume(s), and the heating or

cooling capacity available to each zone. Also, for the building calibration process, the electrical energy demand for the building model is compared to the measured total building energy demand. In order to allow a single variable to represent the energy demand of the entire building model, all energy supplied to the system should be specified as electric, instead of hot water or other supply option. For example, the reheat energy supply for a variable air volume (VAV) or unit ventilator system should specify electric, as should the heating coil energy supply for a multizone air handling system.

For each zone, the supply air volume and heating capacity must also be specified by the user. The supply air volume to each zone is specified based on the building plans or, when available, air flow volumes from flow hood or tracer gas measurements. Building plans specifying the air handling system typically indicate the maximum flow in cfm for each diffuser in the building. The zone volume is the sum of these values for that zone. The system heating capacity for each zone is the same as that determined in the Building Description section for the zone control statement. Recall that this was based on the measured building energy demand, distributed to each zone based on the zone volume. For some systems, such as VAV or unit heaters, this is specified separately for each zone. Other systems specify the total building heating capacity as a single value, such as for a multizone system. In this case, the system heating coil capacity is the sum of the individual zone heating capacities calculated for the Building Description.

In the Fan System Description, the EQUIPMENT SCHEDULES are typically included near the end of that system. Verify that the SYSTEM OPERATIONS are CONSTANT, indicating that the fan system was on during the entire test period. Also, the heating mechanism, whether it be reheat coils or a single heating coil, must be scheduled ON. Again, this verifies that heating was available from the system during the test. Fan operations and other miscellaneous operations should be turned off, and typically are by default, so need not be changed by the user.

During the building calibration, the fan pressures indicated under OTHER SYSTEM PARAMETERS for each system are set to zero. By doing this, the additional energy consumed by the fans to overcome any pressure difference through the system is eliminated from the total building electrical demand. In this section, the DESIRED MIXED AIR TEMPERATURE is also specified. This should be input as the highest zone temperature from the measured data. Using a lower temperature causes BLAST to cool the air, then heat it again to the zone temperatures driving the simulation. During the STEM test, however, no cooling is occurring. The simulation then overestimates the total energy required to maintain the desired indoor air temperature.

### A.1.4    Central Plant

The building central plant(s) is specified in this section of the BLAST input file. Because the actual plant is not evaluated during the analysis, the primary consideration for this input is that the total zone load be met by the plant specified. During heating season tests, a chilling unit is not necessary, and using a simple boiler is appropriate for the building calibration. The user, however, may use the actual building central plant with the appropriate input parameters. In this section the user must also specify the correct Report Writer variable to collect data for the building energy analysis. Details for doing this are given in the next section, Appendix A.1.5.

After the building has been calibrated, the user may wish to evaluate the complete building systems. If the building's actual plant was not used for the calibration, it should be appropriately specified in the BLAST input deck at this time. In any case, adequate plant capacity is required to simulate the building energy performance.

### A.1.5    Report Writer

During the different stages of the building analysis process, the BLAST Report Writer variables must be changed by the user in the *.bin input file. This can be done using either the editor available from the DoBLAST interface, or using any ASCII test editor. During the preliminary stages of the analysis, while initial base building performance is being verified, temperature data from each zone and the total energy demand from the building are required.

The simulated zone temperatures are compared to the measured average zone temperatures, verifying that the temperatures driving the simulation are the similar to those measured during the test. The initial temperature curves may not match exactly, especially during the day. Solar gains during the simulation may cause the base building model temperatures to float above the measured temperatures. This is typically resolved during the analysis process, where the building parameters are changed to better match the energy demand of the model with the measured energy demand. In general, the shape of the simulated temperature curves should be similar to that of the measured temperatures. If not, something is wrong. Also, the base building energy demand should be similar to the measured energy demand. Again, dissimilarities between the two values may exist, but the curve shapes should follow the same general trends.

To collect the data needed for these preliminary comparisons, report variables for each zone and the total building electric demand are required. The temperature

information is generated by specifying zone report variable 24 for each zone, and the building model total energy demand with plant report variable 7. The formats are similar and shown below.

```
   REPORT VARIABLES=(24);    **ZONE TEMPERATURE
OTHER PLANT PARAMETERS:
        REPORT VARIABLES = (7);
   END OTHER PLANT PARAMETERS;
```

The zone variables are typically included as a single line at the end of each zone before the END ZONE statement. The plant variable is typically included at the end of the central plant description before the END PLANT statement. The plant variable must be specified as an OTHER PLANT PARAMETER, as shown in the example. Refer to the sample BLAST input deck in Appendix B to note the exact location.

After running a BLAST simulation, the Report Writer puts the data in an annual.rwd file. From the DoBLAST interface, scroll down to RWFGEN, the Report Writer File Generator. Run this, following the instructions, and selecting all the variables, because those should be the only ones requested in the BLAST input file. You will be asked for an output file name, which should be easy to remember and preferably similar to the general name used for the whole analysis. It should also have a file extension that makes it easy to import into the spreadsheet of choice. For example, Quattro Pro imports *.prn file extensions by default. After executing RWFGEN and getting back to the DoBLAST interface, choose REPWRT. The creates the output file specified in RWFGEN. This file can then be loaded into the spreadsheet and the simulation data compared to the measured data.

Once the performance of the base building has been compared to that of the actual building, and the simulation satisfactory, only the plant report variable is necessary for the analysis. The report variables for the zone temperatures are no longer required, and should either be deleted or commented out. By commenting them out, they can remain in the BLAST input deck and used again with the final building model. Following the same procedure, the user can again compare the measured with the simulated temperatures, observing any shifts in the simulated temperature based on the modifications to the building model. This is not necessary, but can be used to verify that the temperatures driving the simulation continue to resemble the measured values.

## A.2  Weather Data

During the STEM test, measured weather data is also collected. This includes the outdoor ambient temperature (degrees Farenheit), the relative humidity (percentage), the wind speed (mph), the radiation incident on a horizontal surface (Btu/hr per square foot), and the radiation incident on a vertical surface (Btu/hr per square foot), usually the south-facing wall. This raw weather data requires various processing steps before it can be used as a BLAST weather file. First, the horizontal and vertical beam radiation must be converted to beam and diffuse radiation on a horizontal surface. Once the appropriate solar radiation information has been calculated, a file with the raw weather data is converted to BLAST ASCII format using a FORTRAN executable file, and to a BLAST weather file using WIFE, a BLAST program that processes weather data into a usable format. The instructions for this portion follow.

Before beginning the process, determine a name for the weather file that will be used for this building analysis, either based on the building name or building location. This file name should be used during this entire process. From the c:\blastsys\ weather directory, create a subdirectory for the FORTRAN executable code and to use when converting the raw weather file into BLAST ASCII format. We called this directory convert. A weather subdirectory should also be created under the actual building directory to keep the raw weather data and other weather files for future reference. When running WIFE to create the weather file used by BLAST, it is also useful to use this directory, keeping the weather information for each building separate from the remaining files.

### A.2.1  Estimating Beam/Diffuse Radiation Components

Create a weather subdirectory under the building directory to process the measured weather data and keep the weather files separate. The first step toward creating a weather file that BLAST can use is converting the horizontal and vertical radiation measured during the STEM test to beam and diffuse radiation on a horizontal surface. For this project, the TRNSYS Version 13.1 Type 16: Solar Radiation Processor was used to estimate these values [TRNSYS 13.1 Manual]. Developing a separate code specifically to perform this conversion may be an option for the future, but was not created in the scope of the current project.

A complete copy of the TRNSYS input deck is included in Appendix D, with various sections included here for clarity. The following text provides specific information for creating the input deck required for this conversion. However, the TRNSYS 13.1 Manual should be reviewed for more complete technical details of the models used

to make the beam and diffuse radiation estimates. TRNSYS is can be used on a mainframe as well as an IBM or IBM-compatible personal computer. The PC version of TRNSYS 13.1 is essentially the same as the mainframe version.

The beginning of the TRNSYS deck should include information similar to that shown in the example. This is mostly for reference, and is left to the user's discretion.

The assignment statements for a different building will be similar to those in the example, but the names of the files should be changed to reflect the specific building name or location for that analysis. The .DAT file is a single column of the measured horizontal radiation starting at 0100 and including four complete days of data, or 96 hours. The units are in $W/m^2$, and are converted to kJ/hr per square meter, the correct SI units required by TRNSYS, by the Data Reader (as commented in the input deck).

The equation statement section, next in the input deck, is where most of the changes to the input file are made. For this deck, these statements are primarily used to identify each variable used later in the program and to provide a place where most of the changes are made. This section is shown below.

```
*
*   Equations
*
Equations 10
*   simulation period
HSTART=1.0
HSTOP=96.0
TSTEP=1.0
*   parameters for solar radiation processor
DAY=351
LAT=38.5
SC=4871
SHIFT=-1.5
*   inputs to radiation processor
RHO=0.2
SLOPE=0.0
AZIMUTH=0.0
```

The simulation period variables will typically stay the same for different analyses, provided complete measured data is available for 96 hours and that they start at the first hour of the first complete day. The starting time and number of hours should correspond to the data in the .DAT file referenced above. The parameters for the solar radiation processor will typically change, depending on the building location and time of the test. The DAY is the Julian day of the year, LAT is the location

latitude, SC is the solar constant and will not change, and SHIFT is the shift in solar time hour angle. SHIFT should be set to Lst - Lloc, where Lst is the standard meridian for the local time zone and Lloc is the longitude of the test building location. Standard meridians for the continental U.S. time zones are:

- Eastern, 75 degrees west longitude
- Central, 90 degrees west longitude
- Mountain 105 degrees west longitude
- Pacific 120 degrees west longitude.

The building location for the example was at 121.5 degrees west longitude, resulting in the value shown above. The inputs to the radiation processor should not change.

The parameters for TRNSYS Type 9 Input Data Reader should not change, provided the input format for the .DAT file specified above is used.

The parameters and inputs for the Type 16 Solar Radiation Processor should also stay the same from one analysis to another. The variables requiring changes were included in the equation statements. The details of the specific horizontal radiation mode and tilted surface radiation mode, parameters 1 and 3, respectively, can be found in section 4.1.4 of the TRNSYS Version 13.1 User's Manual.

Finally, the Type 25 Printer parameters should also stay the same. The output from this program include three columns of information. The first column is the beam radiation component, the second is the diffuse radiation component, and the third is the measured total radiation on a horizontal surface. The measured data is output to the final file primarily to verify that the estimated beam and diffuse components make sense. All of these values are in kJ/hr per square meter, and must be converted to kBtu/hr per square foot for the next step in this process.

At this point, the TRNSYS output file should be imported into a spreadsheet in which the other weather information is available. The format required for the next step is indicated in the next section.

Many of the variables required for the TRNSYS input deck are also required later to create the final BLAST weather file. We recommend recording this information in a central notebook for future reference.

### A.2.2    Converting to BLAST ASCII

With the above conversion complete, create a raw weather data file (in ASCII) with a *.raw extension. Do not use a *.dat extension, because this must be the extension of the BLAST ASCII file converted by WIFE. The raw data file must be in column format, include two lines of headers/titles (or leave 2 lines blank at the top), and have no tabs. For example, columns in a file copied from a Quattro Pro spreadsheet to an ASCII editor are separated by tabs; replace these with single or double spacing. The file must include seven separate columns with the Julian day(s), hour (0-23 per day), Tout (degrees Farenheit), relative humidity (percentage), Wind (mi/hr), I (beam on a horizontal) and I (diffuse on a horizontal) in Btu/hr per square foot. Verify that the data file begins on the first hour (0100) of the selected day, because the measured data recorded at any one time is from the preceding hour. Verify also that each day includes a full 24 hours of data. Also, one full day of data prior to the comparison period must be included for the analysis. For example, if the comparison period begins at 1400 Friday, a full day of weather data for Thursday must be included in the raw weather data. If complete weather data for that day is not available, use the data from the next day, or the last day. This allows a smooth transition in the simulation from a normal day into the test period. Other required information at this time includes the time zone (i.e., a number between 5 (east coast) and 8 (west coast) for the continental United States), beginning and ending Julian days, month (a number), year (four digits) and the longitude and latitude of the test building location.

With this information, go to the blastsys\weather\convert directory, where a FORTRAN executable file, wet.exe, should exist. This code converts the raw weather data (with the solar radiation conversion completed) into BLAST ASCII format. Copy the raw weather data file into this directory, keeping an original in the weather subdirectory of the building directory in case something goes wrong. To run the executable, enter "wet" and hit return. You will be asked to enter the name of the file with the raw data in it (e.g. weather.raw) and the other parameters listed above. The output from wet.exe is a BLAST ASCII file called out.prn. Rename this file, giving it the *.dat extension required for the final processing stage.

At this point, you should have two *.raw files, an out.prn and a *.dat file. The out.prn file should be identical to the *.dat file and can be deleted. Move the *.dat file to the weather subdirectory of the building. The *.raw file in c:\blastsys\weather\convert can also be deleted, provided the other *.raw file still exists.

### A.2.3    *Weather Information File Encoder*

In the final step, WIFE (Weather Information File Encoder), a BLAST program, processes the BLAST ASCII weather data to produce a file with the weather information in a form that BLAST can use. WIFE can be used to create processed weather files for running BLAST, to modify existing weather files, and to report the status of the data contained on the raw weather file. More about this program can be found in the BLAST user's manuals. For this application, WIFE will be used to read the BLAST ASCII weather data, process it, and create a *.wea file for the specific test period.

WIFE requires two input files. The first is the BLAST ASCII file with the *.dat extension generated above. The second, requiring a *.win extension, is a lead input file with information similar to that needed for the executable. An example from a building in Sacramento, CA is included below. Refer to the BLAST manual for additional information. Note that all capital letters should be used for the TITLE. Both files should have the same prefix and be in the weather subdirectory of the building.

```
TITLE="SACRAMENTO WINTER DATA, DEC 94",
TAPE=(ASCII, 99999),
TIME=8, LAT=38.5, LONG=121.5,
RUN=FROM 16DEC THRU 20DEC,
YEAR=1994,
REPORT, DEFAULTS,
DAILY, HOURLY = FROM 16DEC THRU 20DEC,
```

From the DoBLAST interface, first verify that the current directory is the building weather subdirectory. If not, tab to the right-hand column to change to that directory so that WIFE will deposit the output files into this directory. Tab back to the left-hand column of selections, and choose WIFE. With everything in the right format, two output files with the same prefix as the input files will be generated, *.wot and *.wea. The *.wea file is used by BLAST for the simulation and is in a format difficult to read. The *.wot file is in a readable format and created by WIFE to allow the user to verify that the final weather information is correct. Compare this file to the raw weather data, checking the radiation, wind speed and ambient temperature at various hours to ensure correct processing. Copy the *.wea file to the blastsys\weather directory so that it can be easily accessed when running BLAST.

When using this weather file, the WEATHER TAPE and REPORT FILE information in the BLAST building deck should coincide with the dates of the weather file. See the Lead Input section of Appendix A.1 for more information.

## A.3  Base Building Performance Verification

Before using PERL scripts to run the BLAST simulations and collect the output from each run in a single file, the user must verify that the base building input file can be used by BLAST with no syntax errors, and that the building model temperatures and energy demand are relatively similar to the measured values.

The Report Writer section of this appendix instructs the user in this procedure. After this has been completed, the user must verify that only the Report Writer variable for the central plant electric demand is specified in the BLAST input file.

## A.4  PERL Input Files

A series of PERL scripts were developed to simplify the process of evaluating many parameter variations for each building model. Scripts were used to automate the simulation, data collection and comparison processes. PERL (Practice Extraction and Report Language) was originally designed to assist the Unix user with common tasks not conveniently achieved using the shell and too complicated to code in C or some other Unix tool language [Schwartz, 1993]. Besides Unix systems, PERL was also made available for use in MS/DOS, the version used for this program.

With PERL the user is able to change any specified parameter, invoke BLAST to simulate the modified input deck, collect the data, and compare it to the measured data, calculating the rms error and R metric. A table can then compiled for each run using a DOS batch file, which simply allows all the columns of data from that run to be pasted together into a single output file.

The optimization process uses six PERL scripts. Two scripts, change and simdat, are shells that call the other four scripts, jmodify, rmse, paste, and join. These four scripts perform the required parameter changes and calculations, and organize the results into columns and then tables. Change and simdat are the only scripts called in DOS during the analysis. The specific files and their details are described below. Each script is included in Appendix E.

### change

As mentioned above, this is a shell script that calls the other four scripts to modify the parameter of one or more materials through a range of values, calculated the rms error and the R metric, and tabulate the results. The command line for each call of change must include (in this order): the BLAST input file name (*.bin file), the building specific batch file that invokes BLAST, the measured data file (xxxxmeas.dat), the hour on which the comparison period starts, the number of hours of comparison, the starting fraction of the changing parameter, the final fraction of the changing parameter, the fractional increment, the material name and the parameter of that material to be changed. The specifics for the BLAST batch file and the measured data file are given in Appendix A.5, Optimization Procedure.

Invoking change a single time for one parameter creates a three-column output file with the fractional change, the rmsE error and the R metric. A single run of the analysis involves changing many parameters of the same input file by calling change for each parameter and allowing the resulting three-column output files to be pasted together side-by-side into a single file. The results for a single run can then be easily imported into a spreadsheet and analyzed. A DOS batch file, for which a description and example file are given in Appendix A.5, is used to do this.

Two example command lines to invoke change follow. This line is entered at the DOS prompt, always calling PERL first and then the PERL script.

```
perl change sacr.bin sacr sacrmeas.dat 11 72 0.1 2.0 0.1 DIMENSIONS INTMASSH

perl change ftrileys.bin ftrileys ftrismea.dat 25 42 0.1 2.0 0.1 ROOFINS R
WALLINS R
```

From the first example, the BLAST input file is called sacr.bin, the batch file to invoke BLAST is specified as sacr, and the measured data file is called sacrmeas.dat.

The hour at which the comparison period starts is 11, which refers to 1100 on Saturday for this particular test, and lasts for 72 hours. Referring back to Appendix A.2, the BLAST simulation for this test started on Friday at 0100, with data collected for Saturday through Tuesday, and the comparison period specified within this time frame. For a comparison period that starts after the first 24 hours of the first day, a number greater that 24 is specified. The second example start comparison value, 25, indicates that the comparison period starts at 0100 of the second day of collected data, and compares the data for 42 hours. Using the preceding infor-

mation, this start time would be 0100 on Sunday, and compare the data until 1800 on Monday. The comparison period must fall completely within the data collection period, which is typically four days, or 96 hours.

The starting fraction is usually 0.1, or 10 percent of the parameter minimal value, and the final fraction is 2.0, or 200 percent of the minimal value. The fraction increment is usually 0.1, indicating that the minimal value change in 10 percent increments. This is a general approach and meant as a guideline for the user. Any number of modifications can be made within any range of values. Smaller increments would, of course, require additional time for each run, and larger increments may limit the accuracy of each run of the analysis.

Finally, the material name (ROOFINS) and parameter (R) are indicated, and must coincide with temporary material names used in the BLAST input deck. To change the internal mass surface area, DIMENSIONS is indicated as the material name and INTMASSH is the parameter. Both situations are shown in the example. In the first example, only one material is varied during the analysis. In the second example, one parameter (R) is being varied in both the ROOFINS and WALLINS, changing the R-value in the roof and wall insulation. Note that the parameter must be indicated for both materials. Changing two different parameters for a single material simultaneously defeats the purpose of the analysis, because it obscures the impact each parameter may have on the building energy performance.

The output file from change is called rmseall.out, whether it has been invoked only once or many times using a DOS batch file. As mentioned above, the output of a single call is a three-column file. The example shown below is for a parameter that was changed from 10 percent through 110 percent of the minimal value in 10 percent increments.

```
"fraction"   "TESTGLASS-TRANS"   "R metric"
0.1          15.745              -405.50
0.2          15.448              -375.65
0.3          15.143              -341.66
0.4          15.192              -351.85
0.5          14.858              -308.88
0.6          14.250              -214.27
0.7          14.054              -171.56
0.8          13.901              -126.11
0.9          13.819              -77.75
1            13.753              -22.31
1.1          13.757               38.71
```

Each row is for a single BLAST simulation of the input building model. The first column shows the fractional value that the parameter was changed by for that BLAST simulation, the second column header indicates the material and parameter that were changed for that series of BLAST simulations, but the column itself is the rms error calculated between the measured and simulated energy demand, and the third column is the R metric calculated for each BLAST simulation. When changing many parameters using a batch file, the results from each change are joined side-by-side into a single file. The output file looks like the example above when observed using an ASCII text editor, but was formatted to be imported into a spreadsheet for analysis and plotting.

### simdat

Simdat is also a shell script, similar to change in that the same scripts are used and the command line is the same, except that simdat is called instead of change. This script, however, is used to collect the simulated energy demand output from BLAST. The output can then be used to plot the simulated energy demand versus the measured energy demand, and visually compare the curve shape resulting from different parameter changes to a BLAST input file.

Using a DOS batch file to invoke simdat is also recommended, eliminating the need to retype the command line every time simulated energy demand data is desired. A batch file is easier to modify for each parameter, and only a single file name typed at the DOS prompt to invoke PERL. An example of this batch file is also shown in section A.5.

A sample command line is shown below.

```
perl simdat ftrileys.bin ftrileys ftrismea.dat 25 42 0.7 0.7 0.1 DIMENSIONS
INTMASSH
```

As seen, the format is almost identical to the command line for change. In this case, however, only a single BLAST simulation is desired, so the starting and stopping fractional values are the same. In the above example, the internal mass surface area was decreased to 70 percent of the value in the previous run (not necessarily the base building value). The parameter can be changed as shown in the example, or changed in the *.bin file directly and by specifying 1.0 for the start and stop fractional values in the simdat command line. If the start and stop values are not the same, simdat will run for each incremental change, and save only the energy demand from the last BLAST simulation.

The output from simdat is called answer.out, and is a single column with the
material name, the parameter varied and the percentage by which it was changed,
and the rms error and R metric results from that simulation. The simulated energy
demand is in kBtu/hr, unless SI units were specified in the BLAST input file, and
includes hourly energy demand starting at 0100 of the first day of collected data
through the end of the fourth day, not including the first day actually simulated by
BLAST. This agrees with the information provided above in section A.2. An example
of the output file is included below, showing the header and only the beginning hours
of data.

```
"DIMENSIONS"
"INTMASSH"
"70%"
"RMS error"
  17.287
"R metric"
  -11.18
"******"
          0.0000000
          0.0000000
          0.0000000
          0.0000000
          3.5655959
          3.3080223
          2.7724290
          8.8920536
          7.7718592
         19.0679283
         15.2448387
         16.6923103
         28.8440399
         18.1054363
         20.6896324
         21.4271812
         12.3456173
          9.4444733
```

As with the change output file, this output file was also formatted to be imported
into a spreadsheet for analysis and to be plotted.

### jmodify

This script modifies the BLAST input file directly, changing the parameter value of
the material indicated in the change and simdat command lines. Change calls
jmodify in a loop controlled by the starting and stopping fractional values, changing
the parameter value over the entire specified range.

### rmse

This script calculates the rms error and the R metric for each BLAST simulation. It is called in the same loop as jmodify so that the entire range is covered.

### paste

This script pastes together files of the same length, or more specifically, the three columns of a single output file from change.

### join

This script is similar to paste, but can join files side-by-side with columns of any length. Join is used to collect the three-column files generated by change. Because all parameters may not be varied over the same fractional range and by the same incremental values, this script was created to join columns of any length, inserting a set of double quotes (" ") at the end of the shorter files to correctly maintain the spaces when importing into a spreadsheet.


## A.5  Optimization Procedure

The optimization procedure itself involves manipulating the BLAST building input deck with an ASCII text editor and with the PERL scripts. Once the base building model energy performance has been verified, the PERL scripts can be used to help calibrate the building. The required PERL scripts and base building file should all be copied into a single directory in which all subsequent files will be generated and the entire analysis will take place. The PERL scripts can also be saved in a separate directory, if desired, although no changes to any script is from building to building.

However, two files specific to each building that are called by PERL must first be created. The first is an ASCII text file with the test period and measured data in column format. These can be copied directly from the spreadsheet with the original data into an ASCII text editor. There should be no headers in this file, so that the first line is the first hour of measured data. The name we typically used for this file looked like xxxxmeas.dat, where the xxxx represents the first four letters of the BLAST input file name. The test period should start at 0100 of the first day and with numbering similar to that shown in the following example. Each hour is indicated by the Julian day and the fraction of the day for that hour (eg. 1/24 = 0.042, 2/24 = 0.083, 3/24 = 0.125, etc.). The measured data should be in kBtu/hr when using English units, and kW when using SI units. This should have also been specified in

the BLAST base building deck.  In any case, verify that units are consist through the entire process.

```
64.042      43.63
64.083      43.94
64.125      43.56
64.167      43.77
64.208      51.52
64.250      61.86
64.292      69.03
64.333      88.18
64.375      71.22
64.417      69.68
64.458      65.04
64.500      66.13
```

The first column is the time starting at 0100 on Julian day 64, and the columns are separated by a tab, which occurs by default when copying from the spreadsheet.  The example shows only the hours from 0100 through 1200, which is just the beginning of the file.

The second file called by PERL during the minimization process is a DOS batch file that invokes BLAST and calls the correct weather file for that building.  The only aspect of the batch file that changes for each different building analysis is the weather file that is called.  The following example shows this batch file, with the changing term in bold.  This term should be changed to the name of the *.wea file created for the specific building.  The name we typically used for the batch file was the BLAST input file name, such as ftriley.bat or gunnison.bat.

```
ECHO OFF
CLS
ECHO Moving input files . . .
COPY C:\STEM\STEMAX.BIN IN.DAT
COPY C:\BLASTSYS\WEATHER\FTRIWIN.WEA WTHRFL.DAT
COPY C:\BLASTSYS\BLAST\???lib.sys ???lib.
ECHO Begin BLAST processing . . .
C:\BLASTSYS\BLAST\BLAST.EXE
ECHO Processing complete . . .
ECHO Moving output files . . .
IF EXIST STEMAX.BOT DEL STEMAX.BOT
RENAME OUT.DAT STEMAX.BOT
IF EXIST CLOUT.DAT REN CLOUT.DAT STEMAX.LCI
IF EXIST TCD.DAT REN TCD.DAT STEMAX.TCD
```

```
ECHO Removing extra files .  .  .
DEL in.dat
IF EXIST wthrfl.dat DEL wthrfl.dat
IF EXIST ???lib DEL ???lib.
IF EXIST fort.* DEL fort.*
IF EXIST BLDFL.* DEL BLDFL.*
IF EXIST AHLDFL.* DEL AHLDFL.*
IF EXIST *.scr DEL *.scr
ECHO BLAST run complete.
```

From section A.2 above, a copy of the weather file for the building should also exist in the building weather subdirectory. The line of the batch file can be changed to call the weather file from that directory, but this requires that the entire line be changed for different buildings. The only point here is that the user remember the changes made for a particular building and make the appropriate changes for any subsequent buildings.

At this point, you should be ready to start the first run of the analysis. The most efficient and easiest way to collect the data for each analysis run is by creating a DOS batch file that calls the PERL script 'change' for each parameter, specifying the appropriate command line. Because this batch file typically stays the same for every run, and is simply invoked for subsequent runs until the analysis is done. The batch file looks something like the following example, where the parameter names are those for the particular input deck. These names are the same for all the BLASTED template files, and need not be changed unless multiple wall, roof or internal mass constructions were specified. In any case, the material names should be verified for each new analysis. Also, any secondary parameters should be added to the list. The name we used for this file was chngxxxx.bat, where the x's again refer to four letters of the BLAST input file.

```
ECHO OFF

ECHO changing the sacramento building
IF EXIST rmseall.out DEL rmseall.out
rem the comparison period for the sacramento test starts at 1100 SAT for 72 hours
perl change sacr.bin sacr sacrmeas.dat 11 72 0.1 1.1 0.1 TESTGLASS TRANS
perl change sacr.bin sacr sacrmeas.dat 11 72 0.1 2.0 0.1 ROOFINS R
perl change sacr.bin sacr sacrmeas.dat 11 72 0.1 2.0 0.1 DIMENSIONS INTMASSH
perl change sacr.bin sacr sacrmeas.dat 11 72 0.1 2.0 0.1 EXTBLOCK L
 rem perl change sacr.bin sacr sacrmeas.dat 11 72 0.1 2.0 0.1 EXTBLOCK K
perl change sacr.bin sacr sacrmeas.dat 11 72 0.1 2.0 0.1 INTBLOCK L
 rem perl change sacr.bin sacr sacrmeas.dat 11 72 0.1 2.0 0.1 INTBLOCK K
 rem move rmseall.out sacropt.prn
```

```
move rmseall.out sacrtest.prn
ECHO results in sacrtest.prn

ECHO done running perl stuff
```

The PERL output file from each complete run is called rmseall.out, which is moved to a file specific to the particular building and included before the end of the batch file. The results for each run from the above example will be copied to sacrtest.prn. Each new run will be copied to this file name unless that command line in the batch file is changed for each run. Because the output file after each run is imported and saved into a spreadsheet for evaluation, saving the output file is not critical. If, during the analysis, the user determines that any of the parameters being changed in the batch file do not significantly impact the energy performance of the building, those parameters can be commented out of the batch file using rem. This has been done for the thermal capacitance of EXTBLOCK and INTBLOCK in the example. See Appendix A.4 for details of each command line argument.

After each run, the output file, sacrtest.prn from the example, is imported into a spreadsheet and the minimum rms error for that run determined. An example showing part of an output file after importing into a spreadsheet is included below (Table A.1).

Only the columns and their headings are actually imported into the spreadsheet. For each parameter changed in that run, the fractional values, rms errors and R metric values are shown. The rms error column heading uses the parameter name. The user is responsible for inputting the building name, date and run at the top of the file, or any other information deemed necessary for that run. The user is also left the task of determining the minimum rms error and the percentage by which the rms error changes from the minimal value (100 percent value) for that run.

The rows following the imported file show the minimum rms error and the percent of the minimal value which generated that error, and the last row indicates the change in the rms error for that parameter from the minimal case (100 percent value). For example, column five shows the rms errors calculated when varying the roof insulation R-value from 10 percent to 200 percent. The minimum error between the simulated building energy demand and the measured values is 2.67 kBtu/hr. This is also the error for 100 percent of minimal roof insulation, so the last row for that column is zero. In fact, the example shows that no parameter changes the rms error by more than 2 percent of the minimal value. By this criteria, the modified building from the previous run is the optimized building, and no further analysis is necessary.

**Table A.1. Example of DOS batch file output after importing into spreadsheet.**

Sacramento - first analysis

11June95

run 14

| fraction | TESTGLASS | R metric | fraction | ROOFIN | R metric | fraction | DIMENSION | R metric | fraction | EXTBLO | R metric | fraction | INTBLO | R metric |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.1 | 2.62 | -37.82 | 0.1 | 14.082 | -924.4 | 0.1 | 5.877 | 128.21 | 0.1 | 5.41 | -267.8 | 0.1 | 3.289 | -16.0 |
| 0.2 | 2.619 | -35.48 | 0.2 | 10.949 | -709.5 | 0.2 | 5.312 | 98.98 | 0.2 | 4.769 | -230.0 | 0.2 | 3.138 | -17.31 |
| 0.3 | 2.62 | -32.86 | 0.3 | 8.648 | -547.8 | 0.3 | 4.758 | 76.23 | 0.3 | 4.207 | -196.1 | 0.3 | 2.964 | -7.58 |
| 0.4 | 2.621 | -30.11 | 0.4 | 6.907 | -422.9 | 0.4 | 4.283 | 55.92 | 0.4 | 3.708 | -159.0 | 0.4 | 2.863 | -9.73 |
| 0.5 | 2.624 | -27.29 | 0.5 | 5.571 | -323.5 | 0.5 | 3.855 | 36.42 | 0.5 | 3.308 | -121.1 | 0.5 | 2.813 | -5.5 |
| 0.6 | 2.628 | -24.37 | 0.6 | 4.518 | -235.9 | 0.6 | 3.435 | 20.98 | 0.6 | 3.012 | -90.52 | 0.6 | 2.747 | -7.16 |
| 0.7 | 2.634 | -21.28 | 0.7 | 3.753 | -163.0 | 0.7 | 3.113 | 8.03 | 0.7 | 2.851 | -71.89 | 0.7 | 2.7 | -8.88 |
| 0.8 | 2.641 | -18.02 | 0.8 | 3.175 | -102.3 | 0.8 | 2.862 | -2.82 | 0.8 | 2.735 | -51.16 | 0.8 | 2.671 | -10.8 |
| 0.9 | 2.654 | -14.52 | 0.9 | 2.833 | -55.09 | 0.9 | 2.732 | -1.69 | 0.9 | 2.675 | -32.1 | 0.9 | 2.657 | -12.62 |
| 1 | 2.666 | -11.19 | 1 | 2.666 | -11.19 | 1 | 2.666 | -11.19 | 1 | 2.666 | -11.19 | 1 | 2.666 | -11.19 |
| 1.1 | 2.679 | -7.7 | 1.1 | 2.684 | 26.8 | 1.1 | 2.733 | -20.86 | 1.1 | 2.738 | 7.892 | 1.1 | 2.733 | -10.12 |
| 1.2 | 2.693 | -4.04 | 1.2 | 2.741 | 57.51 | 1.2 | 2.825 | -25.17 | 1.2 | 2.781 | 23.02 | 1.2 | 2.759 | -12.03 |
| 1.3 | 2.71 | -0.45 | 1.3 | 2.857 | 84.81 | 1.3 | 3.046 | -33.75 | 1.3 | 2.837 | 37.05 | 1.3 | 2.79 | -14.18 |
| 1.4 | 2.729 | 3.38 | 1.4 | 3.042 | 113.09 | 1.4 | 3.215 | -42.32 | 1.4 | 2.905 | 50.25 | 1.4 | 2.824 | -16.38 |
| 1.5 | 2.75 | 7.22 | 1.5 | 3.303 | 140.39 | 1.5 | 3.475 | -49.07 | 1.5 | 2.978 | 62.46 | 1.5 | 2.864 | -18.08 |
| 1.6 | 2.772 | 11.12 | 1.6 | 3.473 | 159.7 | 1.6 | 3.65 | -52.7 | 1.6 | 3.066 | 75.73 | 1.6 | 2.907 | -20.43 |
| 1.7 | 2.797 | 15.12 | 1.7 | 3.662 | 179.0 | 1.7 | 3.762 | -59.2 | 1.7 | 3.168 | 89.43 | 1.7 | 2.95 | -21.01 |
| 1.8 | 2.825 | 19.14 | 1.8 | 3.832 | 195.38 | 1.8 | 3.809 | -65.46 | 1.8 | 3.25 | 99.82 | 1.8 | 2.988 | -19.6 |
| 1.9 | 2.85 | 23.07 | 1.9 | 3.996 | 210.39 | 1.9 | 3.87 | -71.81 | 1.9 | 3.332 | 109.81 | 1.9 | 3.034 | -21.08 |
| 2 | 2.88 | 27.39 | 2 | 4.152 | 223.64 | 2 | 3.862 | -73.15 | 2 | 3.413 | 119.43 | 2 | 3.146 | -20.31 |

minimum

| RMS err | 2.619 | | 100% | 2.666 | | 120% | 2.666 | | 100% | 2.666 | | 90% | 2.657 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| %smaller | 1.76 | | | 0.00 | | | 0.00 | | | 0.00 | | | 0.34 | |

This, however, is not often the case for the first few runs of a typical analysis. When the convergence criteria indicate that another run is necessary in the calibration process, the user must change the parameter value in the BLAST input deck and use this modified deck for the next run. Comment statements at the very beginning of the input file can include useful reference information including the run number, the date changes were made, the new parameter values and the percent change from the minimal value. As mentioned earlier, the actual minimal value may be indicated as a comment statement following the material definition. Before making changes in the deck, an separate copy of the base building deck should be saved.

This modified BLAST input deck, with the same file name, is now used for Run 2 of the analysis by invoking the correct batch file. The second output file can be imported into the same spreadsheet file, correctly labeled and evaluated. This process continues until the rms error no longer changes by more than 2 percent from the previous run. At this point, the analysis of this building is complete, and the optimized building file saved.

To plot the simulated energy demand compared to the measured energy demand for the base and final building models, or any modified building energy demand during the analysis, the simdat PERL script is used. The command line for this file is almost identical to that of change, with only the name of the script changing. During the analysis, we created a DOS batch file, called runopt.bat, to invoke simdat to avoid typing in the command line every time. To get the output for the base building, the user can specify a fraction of 1.0 for both the start and stop values and any material and parameter in the command line. An example follows.

```
ECHO OFF
ECHO collecting energy data for plotting - ftriley building
perl simdat ftriley.bin ftriley ftrimeas.dat 20 57 1.0 1.0 0.1 DIMENSIONS
INTMASSH
move answer.out runopt.prn
ECHO energy demand results for latest run in runopt.prn
```

As for the output from the chngxxxx.bat batch file, the results from this file are imported into a spreadsheet for plotting or other analysis. The header for this output file includes the material name, the modified parameter, the rms error and the R metric.

# Appendix B: BLAST Input Deck for Bell Avenue School

The BLAST input file shown here uses a single zone to model a single wing of a school located in Sacramento, California. The deck has been changed during the analysis, with comment statements noting the modifications.

```
*|*                        SACRAMENTO BELL AVENUE SCHOOL
*|*
*|*
*|*                        Date:|04 June 95
*|*                    Filename:|sacr.bin
*|*
**   changing parameters based on curve fit, not just rmsE minimum
**01  08June95 - ROOFINS R=2.57 (25.7% of minimal)
**02  08June95 - DIMENSIONS INTMASSW=369.6 (200% of minimal)
**03  08June95 - DIMENSIONS INTMASSW=739.2 (400% of minimal)
**04  09June95 - INTBLOCK L=0.261 (39.1% of minimal)
**05  09June95 - DIMENSIONS INTMASSW=1000.1 (541.2% of minimal)
**06  09June95 - ROOFINS R=3.19 (31.9% of minimal)
**07  10June95 - TESTGLASS TRANS=0.14 (16.3% of minimal)
**08  10June95 - INTBLOCK L=0.139 (20.9% of minimal)
**09  10June95 - ROOFINS R=3.64 (36.4% of minimal)
**10 10June95 - DIMENSIONS INTMASSW=1201.8 (650.3% of minimal)

 BEGIN INPUT;
   RUN CONTROL:
NEW ZONES,
NEW AIR SYSTEMS,
PLANT,
**      DESIGN SYSTEMS,
**      DESIGN PLANT,
UNITS(IN=ENGLISH, OUT=ENGLISH);
TEMPORARY MATERIALS:
  ROOFINS
    = (R=3.64,ABS=0.75,TABS=0.900,VERY ROUGH);
**minimal R=10.00
  EXTBLOCK  **CB57 - exterior wall
    = (L=0.6670,K=0.2420,D=77.0,CP=0.200,ABS=0.20,
    TABS=0.900,MEDIUM ROUGH);
  INTBLOCK  **CB57 - interior wall/internal mass construction
    = (L=0.139,K=0.2420,D=77.0,CP=0.200,ABS=0.20,
    TABS=0.900,MEDIUM ROUGH);
      **minimal L=0:667
  TESTGLASS
```

```
     = (R=0.047,ABS=0.75,TABS=0.900,TRANS=0.14,FILMTRANS=0.00,
       IR=1.52,VERY SMOOTH,GLASS);
END;
TEMPORARY WALLS:
  EXTWALL1
     = (CO27 ,                 **stucco
       B1 ,                    **airspace resistance, R=0.91
       EXTBLOCK ,
       B1 ,
       E8);                    **5/8" gyp board
  EXTWALL2                     **north wall, 12" deep cabinets built into wall
     = (CO27 ,                 **stucco
       B1 ,
       EXTBLOCK ,
       B1 ,
       E8 ,
       B1 ,
       B1);
  INTWALL
     = (E6 ,                   **1/2" sheathing board
       B1 ,
       INTBLOCK ,
       B1 ,
       E6);
END;
TEMPORARY ROOFS:
  TEMPROOF
     = (RF4 ,                  **3/8" building membrane
       ROOFINS ,
       E8);
END;
TEMPORARY FLOORS:
  TEMPFLOOR
     = (DIRT 12 IN ,
       CO22 ,
       FF5);
END;
TEMPORARY WINDOWS:
  TEMPWINDOW
     = (TESTGLASS ,
       AR4 ,
       TESTGLASS);
END;
TEMPORARY SCHEDULE (POWERIN):
**   tues=wed=thurs=most of friday;
  FRIDAY = (0 to 2 - 0.04, 2 to 3 - 0.05, 3 to 4 - 0.07, 4 to 5 - 0.10,
             5 to 6 - 0.13, 6 to 7 - 0.18, 7 to 8 - 0.22, 8 to 9 - 0.19,
             9 to 10 - 0.18, 10 to 11 - 0.15, 11 to 12 - 0.05, 12 to 18 -
             0.04, 18 to 19 - 0.29, 19 to 20 - 0.4, 20 to 21 - 0.05, 21
             to 24 - 0.0),
  SATURDAY = (0 to 8 - 0.00, 8 to 9 - 0.01, 9 to 10 - 0.89, 10 to 11 -
               1.00, 11 to 12 - 0.92, 12 to 13 - 0.82, 13 to 14 - 0.75,
               14 to 15 - 0.71, 15 to 16 - 0.67, 16 to 17 - 0.69, 17 to 18
               - 0.68, 18 to 19 - 0.66, 19 to 21 - 0.72, 21 to 22 - 0.74,
               22 to 23 - 0.72, 23 to 24 - 0.74),
  SUNDAY = (0 to 1 - 0.74, 1 to 2 - 0.76, 2 to 4 - 0.73, 4 to 5 - 0.75, 5
```

```
                   to 6 - 0.73, 6 to 8 - 0.75, 8 to 9 - 0.70, 9 to 10 - 0.64, 10
                   to 11 - 0.60, 11 to 12 - 0.45, 12 to 13 - 0.34, 13 to 14 -
                   0.28, 14 to 15 - 0.35, 15 to 16 - 0.45, 16 to 17 - 0.49, 17 to
                   19 - 0.53, 19 to 20 - 0.55, 20 to 21 - 0.58, 21 to 22 - 0.60,
                   22 to 23 - 0.58, 23 to 24 - 0.59),
        MONDAY = (0 to 1 - 0.64, 1 to 2 - 0.69, 2 to 4 - 0.70, 4 to 5 - 0.71, 5
                   to 6 - 0.70, 6 to 7 - 0.67, 7 to 8 - 0.66, 8 to 9 - 0.63, 9 to
                   10 - 0.57, 10 to 11 - 0.52, 11 to 12 - 0.46, 12 to 13 - 0.42,
                   13 to 15 - 0.37, 15 to 16 - 0.39, 16 to 17 - 0.44, 17 to 19 -
                   0.48, 19 to 20 - 0.49, 20 to 21 - 0.50, 21 to 22 - 0.54, 22 to
                   23 - 0.51, 23 to 24 - 0.04),
        TUESDAY = (0 to 2 - 0.04, 2 to 3 - 0.05, 3 to 4 - 0.07, 4 to 5 - 0.10,
                    5 to 6 - 0.13, 6 to 7 - 0.18, 7 to 8 - 0.22, 8 to 9 - 0.19,
                    9 to 10 - 0.18, 10 to 11 - 0.15, 11 to 12 - 0.05, 12 to 17
                    - 0.04, 17 to 24 - 0.03),
      WEDNESDAY = (0 to 24 - 0.03),
      THURSDAY = TUESDAY,
      HOLIDAY = MONDAY;
   END;
   TEMPORARY SCHEDULE (INFILT):
      SATURDAY = (0 to 19 - 0.30, 19 to 20 - 0.45, 20 to 22 - 0.26, 22 to 24
                   - 0.57),
      SUNDAY = (0 to 1 - 0.60, 1 to 2 - 0.72, 2 to 3 - 0.56, 3 to 4 - 0.54, 4
                  to 5 - 0.60, 5 to 6 - 0.54, 6 to 7 - 0.58, 7 to 8 - 0.59, 8 to
                  10 - 0.41, 10 to 11 - 0.23, 11 to 12 - 0.41, 12 to 13 - 0.37,
                  13 to 14 - 0.33, 14 to 15 - 0.38, 15 to 16 - 0.46, 16 to 17 -
                  0.44, 17 to 18 - 0.43, 18 to 19 - 0.39, 19 to 20 - 0.41, 20 to
                  21 - 0.42, 21 to 22 - 0.38, 22 to 23 - 0.34, 23 to 24 - 0.37),
      MONDAY = (0 to 4 - 0.37, 4 to 5 - 0.36, 5 to 6 - 0.37, 6 to 7 - 0.36, 7
                  to 8 - 0.35, 8 to 10 - 0.39, 10 to 11 - 0.43, 11 to 12 - 0.36,
                  12 to 13 - 0.32, 13 to 16 - 0.33, 16 to 17 - 0.30, 17 to 18 -
                  0.31, 18 to 19 - 0.30, 19 to 21 - 0.31, 21 to 22 - 0.33, 22 to
                  23 - 0.00, 23 to 24 - 0.13),
      TUESDAY = (0 to 1 - 0.26, 1 to 2 - 0.25, 2 to 3 - 0.26, 3 to 4 - 0.23,
                   4 to 6 - 0.26, 6 to 7 - 0.30, 7 to 10 - 0.34, 10 to 11 - 0.38,
                   11 to 12 - 0.86, 12 to 13 - 0.70, 13 to 14 - 0.67, 14 to 15 -
                   0.64, 15 to 16 - 0.00, 16 to 17 - 0.00, 17 to 20 - 0.26, 20
                   to 21 - 0.30, 21 to 22 - 0.32, 22 to 23 - 0.31, 23 to 24 -
                   0.32),
      WEDNESDAY = (0 to 1 - 0.31, 1 to 3 - 0.30, 3 to 5 - 0.29, 5 to 6 - 0.35,
                     6 to 7 - 0.30, 7 to 10 - 0.34, 10 to 11 - 0.38, 11 to 12 -
                     0.86, 12 to 13 - 0.70, 13 to 14 - 0.67, 14 to 15 - 0.64, 15
                     to 16 - 0.00, 16 to 17 - 0.00, 17 to 20 - 0.26, 20 to 21
                     - 0.30, 21 to 22 - 0.32, 22 to 23 - 0.31, 23 to 24 - 0.32),
      THURSDAY = TUESDAY,
      FRIDAY = TUESDAY,
      HOLIDAY = MONDAY;
   END;
   TEMPORARY CONTROLS (MZ1):
      PROFILES:
         p57=(1.0 at 56.5, 0.0 at 57.5);
         p58=(1.0 at 57.5, 0.0 at 58.5);
         p59=(1.0 at 58.5, 0.0 at 59.5);
         p60=(1.0 at 59.5, 0.0 at 60.5);
         p61=(1.0 at 60.5, 0.0 at 61.5);
         p63=(1.0 at 62.5, 0.0 at 63.5);
```

```
        p64=(1.0 at 63.5, 0.0 at 64.5);
        p66=(1.0 at 65.5, 0.0 at 66.5);
        p67=(1.0 at 66.5, 0.0 at 67.5);
      SCHEDULES:
        FRIDAY=(0 to 1 - p61, 1 to 3 - p60, 3 to 11 - p59, 11 to 12 - p66, 12
                to 15 - p67, 15 to 16 - p66, 16 to 17 - p64, 17 to 19 - p63, 19
                to 20 - p66, 20 to 21 - p64, 21 to 22 - p63, 22 to 24 - p61),
        SATURDAY=(0 to 1 - p61, 1 to 3 - p60, 3 to 5 - p59, 5 to 7 - p58, 7 to
                  9 - p57, 9 to 10 - p60, 10 to 11 - p63, 11 to 24 - p64),
        SUNDAY=(0 to 24 - p64),
        MONDAY=(0 to 23 - p64, 23 to 24 - p63),
        TUESDAY=(0 to 1 - p61, 1 to 3 - p60, 3 to 11 - p59, 11 to 12 - p66, 12
                 to 15 - p67, 15 to 16 - p66, 16 to 17 - p64, 17 to 18 - p63,
                 18 to 19 - p61, 19 to 20 - p60, 20 to 22 - p59, 22 to 24 -
                 p58),
        WEDNESDAY=(0 to 6 - p57, 6 to 11 - p59, 11 to 12 - p66, 12 to 15 - p67,
                   15 to 16 - p66, 16 to 17 - p64, 17 to 18 - p63, 18 to 19 -
                   p61, 19 to 20 - p60, 20 to 22 - p59, 22 to 24 - p58),
        THURSDAY=TUESDAY,
        HOLIDAY=MONDAY;
  END CONTROLS;
  PROJECT="SMUD - Sacramento School Building";
  LOCATION=SACRAM ;
  *     DESIGN DAYS=SACRAMENTO CALIFORNIA SUMMER,
  *                 SACRAMENTO CALIFORNIA WINTER;
  WEATHER TAPE FROM 16DEC THRU 20DEC;
  *          Thurs (JDAY=350) - Tues (JDAY=354)
  REPORT FILE FROM 16DEC THRU 20DEC;
  GROUND TEMPERATURES=(54, 55, 58, 62, 67, 74, 72, 68, 64, 62, 58, 55);
      BEGIN BUILDING DESCRIPTION;
  DIMENSIONS:
    WIDTH1=160.0,             **north/south-facing walls
    HEIGHT1=11.0,
    WIDTH2=24.0,              **east/west-facing walls
    HEIGHT2=11.0,
    INTMASSW=1201.8,          **minimal = 184.8
    INTMASSH=10.0;
  BUILDING="Bell Avenue School, SMUD ";
    NORTH AXIS=0.00;
    HEAT BALANCE=2;
    SOLAR DISTRIBUTION=0;
    ZONE 1 "SCHOOL ROOMS":
      ORIGIN:(0.00, 0.00, 0.00);
      NORTH AXIS=0.00;
      EXTERIOR WALLS :
        STARTING AT(0.00, 0.00, 0.00)
        FACING(180.00)
        TILTED(90.00)
        EXTWALL1 (WIDTH1 BY HEIGHT1)
          WITH WINDOWS OF TYPE
          TEMPWINDOW (76.0 BY 2.5)                              **WINDOW
  ABOVE 9' OVERHANG
            REVEAL(0.00)
            AT (15,8.25)
          WITH WINDOWS OF TYPE
```

```
                TEMPWINDOW (9.0 BY 2.25)                                    **WINDOW
        IN THE DOOR (BELOW OVERHANG)
                REVEAL(0.00)
                 AT (15,4)
               WITH OVERHANGS (WIDTH1 BY 1.667)
                 AT (0.0,11.0)
               WITH OVERHANGS (WIDTH1 BY 9.0)
                 AT (0.0, 8.0),
             STARTING AT(WIDTH1, 0.00, 0.00)
             FACING(90.00)
             TILTED(90.00)
             EXTWALL1 (WIDTH2 BY HEIGHT2)
               WITH OVERHANGS (WIDTH2 BY 9.0)
                 AT (0.0,8.0),
             STARTING AT(WIDTH1, WIDTH2, 0.00)
             FACING(0.00)
             TILTED(90.00)
             EXTWALL1 (WIDTH1 BY HEIGHT1)
               WITH WINDOWS OF TYPE
               TEMPWINDOW (101.33 BY 6.0)
                 REVEAL(0.00)
                 AT (15.0,3.0)
               WITH OVERHANGS (WIDTH1 BY 1.667)
                 AT (0.0, 11.0),
             STARTING AT(0.00, WIDTH2, 0.00)
             FACING(270.00)
             TILTED(90.00)
             EXTWALL1 (WIDTH2 BY HEIGHT2)
               WITH OVERHANGS (WIDTH2 BY 9.0)
                 AT (0.0, 8.0);
           SLAB ON GRADE FLOORS :
             STARTING AT(0.00, WIDTH2, 0.00)
             FACING(180.00)
             TILTED(180.00)
             TEMPFLOOR (WIDTH1 BY WIDTH2);
           ROOFS :
             STARTING AT(0.00, 0.00, HEIGHT1)
             FACING(180.00)
             TILTED(0.00)
             TEMPROOF (WIDTH1 BY WIDTH2);
           INTERNAL MASS: INTWALL
             ( INTMASSW BY INTMASSH);
           PEOPLE= 0.0, OFF,
             AT ACTIVITY LEVEL 0.45, 30.00 PERCENT RADIANT,
               FROM 01JAN THRU 31DEC;
           LIGHTS= 0.00, OFF,
               00.00 PERCENT RETURN AIR, 20.00 PERCENT RADIANT,
               20.00 PERCENT VISIBLE, 0.00 PERCENT REPLACEABLE,
               FROM 01JAN THRU 31DEC;
           INFILTRATION = 326.9, INFILT,
             WITH COEFFICIENTS (1,0,0,0),
             FROM 01JAN THRU 31DEC;
    *           EQUIPMENT = 52.03, POWERIN,    **kBtu/hr, maximum load
    *              0.0 PERCENT RADIANT, 0.0 PERCENT LATENT, 0.0 PERCENT LOST,
    *              FROM 01JAN THRU 31DEC;
           CONTROLS=MZ1, 3412000.0 HEATING, 3412000.0 COOLING,
```

```
            0.00 PERCENT MRT, FROM 01JAN THRU 31DEC;
**     REPORT VARIABLES=(24,25);
  END ZONE;
   END BUILDING DESCRIPTION;
   BEGIN FAN SYSTEM DESCRIPTION;
UNIT VENTILATOR SYSTEM 1
"system1 " SERVING ZONES
    1;
  FOR ZONE 1:
    SUPPLY AIR VOLUME=700.0;
    EXHAUST AIR VOLUME=0;
    REHEAT CAPACITY=55.0;
    REHEAT ENERGY SUPPLY=ELECTRIC;
    BASEBOARD HEAT CAPACITY=0.0;
    BASEBOARD HEAT ENERGY SUPPLY=HOT WATER;
    ZONE MULTIPLIER=1;
  END ZONE;
  OTHER SYSTEM PARAMETERS:
    SUPPLY FAN PRESSURE=0.0;   ** DEFAULT=2.48914;
    SUPPLY FAN EFFICIENCY=0.7;
    RETURN FAN PRESSURE=0.0;
    RETURN FAN EFFICIENCY=0.7;
    EXHAUST FAN PRESSURE=0.0; ** DEFAULT=1.00396;
    EXHAUST FAN EFFICIENCY=0.7;
    MIXED AIR CONTROL=FIXED PERCENT;
    DESIRED MIXED AIR TEMPERATURE=COLD DECK TEMPERATURE;
    OUTSIDE AIR VOLUME=0.0;
    PREHEAT COIL LOCATION=NONE;
    PREHEAT TEMPERATURE=46.4;
    PREHEAT ENERGY SUPPLY=HOT WATER;
    PREHEAT COIL CAPACITY=0;
    GAS BURNER EFFICIENCY=0.8;
    HUMIDIFIER TYPE=NONE;
    HUMIDISTAT LOCATION=1;
    HUMIDISTAT SET POINT=50;
    SYSTEM ELECTRICAL DEMAND=0.0;
    REHEAT TEMPERATURE CONTROL=FIXED SET POINT;
    REHEAT TEMPERATURE LIMIT=140;
    REHEAT CONTROL SCHEDULE=(140 AT 0,70 AT 70);
** FOR DESIGN SYSTEM
    COOLING SAT DIFFERENCE =20;
    HEATING SAT DIFFERENCE =70;
    AIR VOLUME COEFFICIENT =1;
  END OTHER SYSTEM PARAMETERS;
  EQUIPMENT SCHEDULES:
    SYSTEM OPERATION=ON,FROM 01JAN THRU 31DEC;
    EXHAUST FAN OPERATION=OFF,FROM 01JAN THRU 31DEC;
    PREHEAT COIL OPERATION=OFF,FROM 01JAN THRU 31DEC;
    HUMIDIFIER OPERATION=OFF,FROM 01JAN THRU 31DEC;
    REHEAT COIL OPERATION=ON,FROM 01JAN THRU 31DEC;
    TSTAT BASEBOARD HEAT OPERATION=OFF,FROM 01JAN THRU 31DEC;
    HEAT RECOVERY OPERATION=OFF,FROM 01JAN THRU 31DEC;
    MINIMUM VENTILATION SCHEDULE=MINOA,FROM 01JAN THRU 31DEC;
    MAXIMUM VENTILATION SCHEDULE=MAXOA,FROM 01JAN THRU 31DEC;
    SYSTEM ELECTRICAL DEMAND SCHEDULE=OFF,FROM 01JAN THRU 31DEC;
  END EQUIPMENT SCHEDULES;
```

```
END SYSTEM;
   END FAN SYSTEM DESCRIPTION;
   BEGIN CENTRAL PLANT DESCRIPTION;
PLANT 1 "plant " SERVING ALL SYSTEMS;
  EQUIPMENT SELECTION:
    RECIPROCATING CHILLER :
        4 OF SIZE 10;
    SIMPLE BOILER :
        4 OF SIZE 13.2;
  END EQUIPMENT SELECTION;
  PART LOAD RATIOS:
    RECIPROCATING CHILLER(MIN=.10,MAX=1.05,BEST=.65,ELECTRICAL=.2275);
  END PART LOAD RATIOS;
  SCHEDULE:
    PLANT ELECTRICAL DEMAND=0.0,CONSTANT,FROM 1JAN THRU 31DEC;
    PROCESS WASTE HEAT=0.0,CONSTANT,FROM 1JAN THRU 31DEC,AT LEVEL 5;
  END SCHEDULE;
  SCHEDULE:
    HOT WATER=0.0,CONSTANT,FROM 1JAN THRU 31DEC,
                    AT 125.0 SUPPLIED BY SIMPLE BOILER;
  END SCHEDULE;
  SPECIAL PARAMETERS:
    TCOOL=44.00600000;
    RWCRC=124.82266667;
    BOILEF=0.75;
    BOLELE=0.0;
  END SPECIAL PARAMETERS;
  EQUIPMENT PERFORMANCE PARAMETERS:
    RPWR3C (0.14940000, 0.95680000, -0.11184000);
    ADJT3C (95.00000000, 2.50000000, 44.00000000);
    RCAV3C (1.01846000, -0.03075000, -0.00014420);
    ADJE3C (2.32010000, -1.46175000, 0.18148700);
  END EQUIPMENT PERFORMANCE PARAMETERS;
  FOR SYSTEM 1:
    SYSTEM MULTIPLIER=1;
  END SYSTEM;
  OTHER PLANT PARAMETERS:
    REPORT VARIABLES=(7);
  END OTHER PLANT PARAMETERS;
END PLANT;
   END CENTRAL PLANT DESCRIPTION;
 END INPUT;
```

# Appendix C: BLASTED Basic User's Manual

Table of Contents

## C.1  BLASTED Overview

BLASTED is a program used to modify specially prepared BLAST input files. It provides an easy way for users to change numbers and text in the BLAST input file and gives users context sensitive on line help. It also provides extensive menus so that users do not have to be concerned about names and spelling.

There are five BLAST input files, called BLAST template files, that are supplied with the BLASTED software. These are input files describing buildings of varying complexity. Descriptions of these buildings are given in the following section. This User's Manual also includes instructions for loading and running BLASTED.

BLASTED commands all start with an asterisk (*). Because BLAST treats all lines beginning with an asterisk as comments, BLASTED commands can be embedded in a BLAST input deck. Any line that starts with the character combination *| (an asterisk and a vertical line) is interpreted as an input command to BLASTED. The BLASTED Super User's Manual describes the BLASTED commands in detail.

## C.2  Loading BLASTED

BLASTED runs under the DOS operating system or in a DOS window. To load the BLASTED system, the user should copy all the files on the disk to the directory on the hard drive where you want to have BLAST input file kept. The DOBLAST utility supplied with the BLAST software system expects input files in the BLASTSYS directory. If you do not want to change this, copy all of the BLASTED software into the BLASTSYS directory. Another approach that keeps files separate is to make a BLASTED subdirectory under BLASTSYS. You can change the defaults in DOBLASTED to look for input files in this new subdirectory.

The above instructions make finding the BLASTED/BLAST input files simple. Actually, you can put BLASTED anywhere you want. You can change directories when you open BLASTED/BLAST input files from within BLASTED. BLASTED only needs to have the .dat and help.hlp files in its directory.

The five template BLAST input files all have .bin sufixes. You can copy and rename the template you need for a particular project so that you do not modify the original templates.

## C.3  Template BLAST Input Files

### *1zone.bin*

The 1zone.bin file is a simple one-story, one-zone model.  It has four exterior walls, a roof and a slab on grade floor.  Each exterior wall has a window.  If your project building has no windows or windows in fewer than four walls, give window dimensions of zero for walls with no windows.

### *5zn1sto.bin*

5zn1sto.bin is five zone model of a one-story building.  There are four perimeter zones and one interior zone.  Each perimeter zone has one exterior wall and three partitions.  All zones have a roof and slab on grade floor.  A floor plan of the building is shown below along with the zone numbering scheme. Users supply input for the south and east zones and the interior zone.  The north zone is a rotated version of the south zone and the west zone is a rotation of the east zone.

### *10znmsto.bin*

The 10znmsto.bin is similar to 5zn1sto.bin except it is for a multistory building. There are five zones on the top floor as shown in Figure C.1.  Zones six through ten have corresponding locations on the intermediate floor.
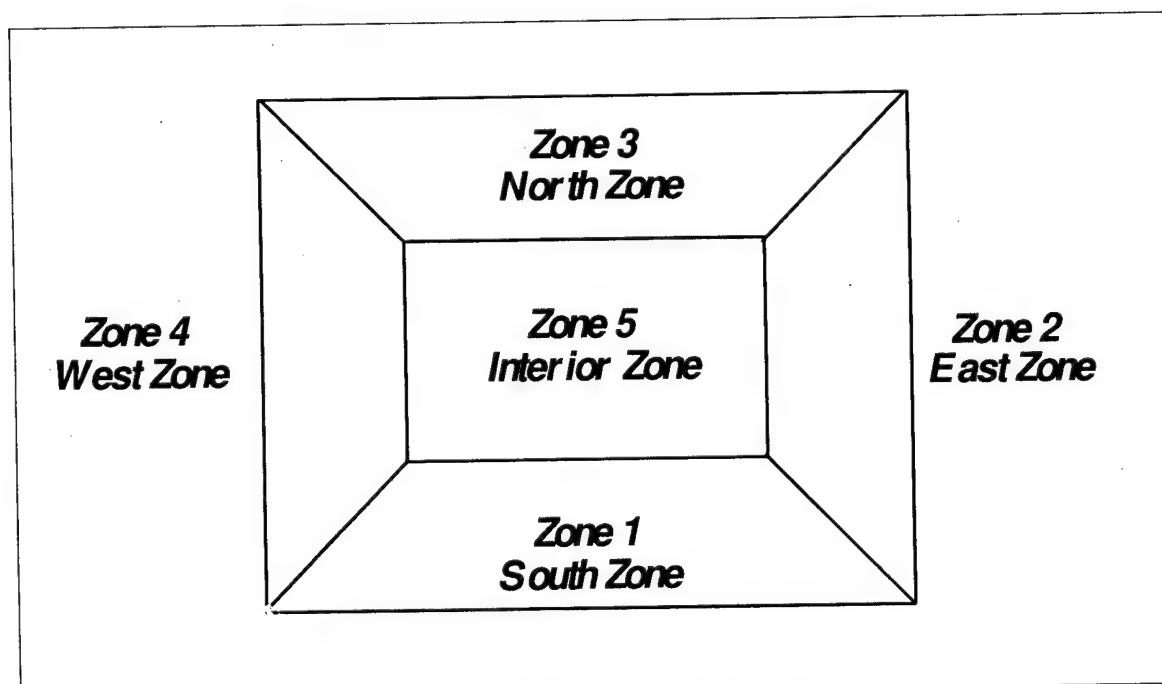


**Figure C.1.  Plan of the five zone, one story BLAST/BLASTED Template.**

There is one fan system per floor. Users can use the system multiplier for system 2 to model an arbitrary number of intermediate floors.

Zones one through five have a roof while zones six through ten have ceilings. It was assumed that the first story has negligible floor losses so a FLOOR was specified for all zones.

### 1storymz.bin

The 1storymz.bin template is a nine-zone building, one zone at each corner with two exterior walls and two interior partitions, one zone on each of the four sides of the building with one exterior wall and three interior partitions, and one interior zone. The plan and zone numbering scheme are shown below. Each zone has a roof and slab on grade floor.

There is one fan system for the building.

Users describe the details of zones 1, 5 and 9. Zone 1 is rotated to make zone 2, 3 and 4 and zone 5 is rotated to form zones 6, 7, and 8.

For zone 5, 6, 7 and 8 users can describe one small scale zone like those shown in the Figure C.2 and use the ZONE MULTIPLIER when describing the air-handling system or users can describe one long zone on each exposure. The former is recommended, especially for load calculations.

### multisto.bin

This input file template is the multistory version of 1storymz.bin. The top floor is configured as shown in Figure C.2. The intermediate floors contain zones ten through eighteen. Zone 10 is below zone 1, zone 11 is below zone 2 and so on.

As in 10znmsto.bin there is one fan system per floor. Again, zone multipliers can be used as appropriate, and system multipliers can be used to simulate multiple intermediate floors.

## C.4  Running BLASTED

Running BLASTED is very simple. From whatever directory BLASTED is kept in, simply type BLASTED. The BLASTED program opens a window with appropriate menus. After clicking "OK" on the title window, click on the FILE menu and select
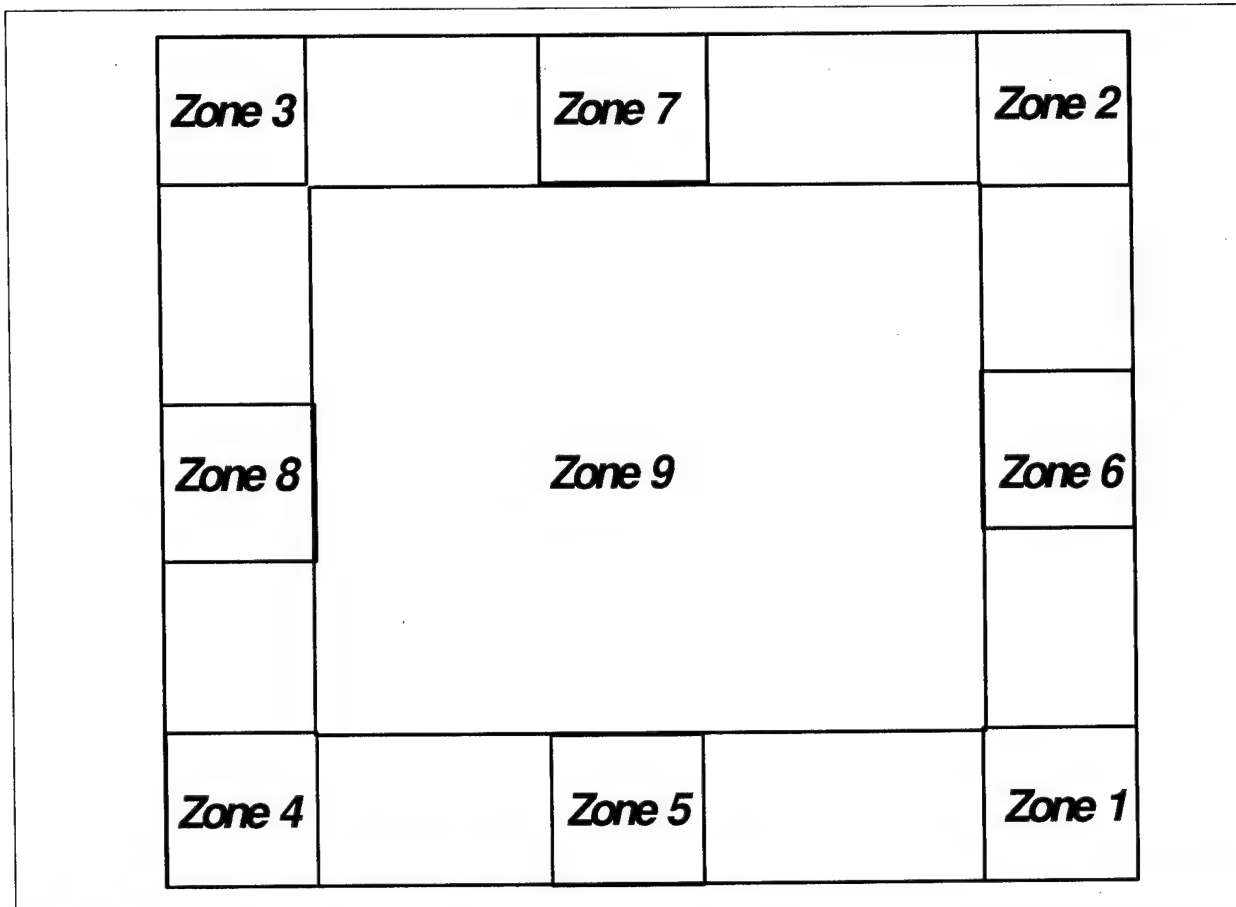
**Figure C.2.** **Plan of the nine zone, one story BLAST/BLASTED template.**

"Open" (or hit the F3 function key). A list of .bin file in the current directory will appear. You can select on of these files or select another directory. Select "..\" to move up a level in your directories.

Once you have found the appropriate input file, double click on it or high light it and click on "open". Opening the large files may take a moment on all but the fastest computers. The screen will fill with fields and text. You can move from field to field with the arrow keys or use the mouse to click on a field.

Perhaps the best way to become aquainted with BLASTED is to open one of the templates. To continue, copy the template 1zone.bin to another file called, for example, tutor.bin. Launch BLASTED as described above and open tutor.bin.

The fields named "DATE:" and "Filename" are essentially comments and can be changed as the user sees fit.

The next line have fields next to "DESIGN SYSTEMS?" and "DESIGN PLANTS?". Clicking on either of these fields produces a menu from which the user must choose. If a user highlights the field (presses cancel if the menu appears or use the arrow keys to highlight the field) and then presses the F1 function key, a context sensitive help window will appear with additional instructions.

Moving down the available fields the user can select layer of the exterior wall from a list of available layer from the BLAST library. Again, menu choices keep the user from entering any text that BLAST would not accept. The user need only define as many new structures (walls, roofs, floors, etc.) that they plan to use later in describing the building zones.

Moving down in the BLASTED file, users are allowed to select design days, location, and the simulation period, all menu selection inputs.

Building dimensions are selected next. These are numeric inputs where the user types in a new number to replace the old. Here, range checking and units conversion may be made by BLASTED. Only numbers within the allowable range can be input.

Basically, all the remaining highlighted fields that the user can change are either free text (names, titles, etc.), menu inputs that the user picks from menu files, or numeric input where the user changes a number that is range checked. For most (hopefully all) fields, pressing the F1 function key will launch a help window to guide the user.

Once you have scanned through the whole file, changing data to customize your input, exit BLASTED using the FILE menu and then launch DOBLAST to run BLAST.

BLASTED also has a plotting capability. BLASTED expects data for plotting to be tab or space deliminited columns with the first row (only) containing column headings. The data files must have a .plt extension. You can choose to imbed report writer commands in your BLAST template files and then use the REPORT WRITER program to produce columns of data. Using an editor, users must then remove the rows in the REPORT WRITER output file containing the variable description data, leaving only columns of data with their column headings in row one. Save the edited file with a .plt extension. Launch BLASTED again and select "New Plot" from the PLOT menu. Follow the instructions to generate a plot of your choice.

In summary, BLASTED is a useful way to get going quickly and to modify standard files to create project specific BLAST input.

# Appendix D: BLASTED Super User's Manual

Table of Contents

## D.1  BLASTED Overview

BLASTED is a program used to modify specially prepared BLAST input **files. It** provides an easy way for users to change numbers and text in the BLAST **input file** and gives users context sensitive on line help. It also provides extensive **menus so** that users do not have to be concerned about names and spelling.

There are five BLAST input files, called BLAST template files, that are **supplied with** the BLASTED software. These are input files describing buildings **of varying** complexity. Descriptions of these buildings are given in the BLASTED **User's** Manual. The User's Manual also includes instructions for loading **and running** BLASTED. It is assumed that super users will read the User's **Manual before** reading this Super User's Manual.

BLASTED commands all start with an asterisk (*). Because BLAST treats **all lines** beginning with an asterisk as comments, BLASTED commands can be **embedded in** a BLAST input deck. Any line that starts with the character combination *I **(an** asterisk and a vertical line) is interpreted as an input command to **BLASTED.** BLASTED command syntax is shown in the section that follows.

## D.2  BLASTED Commands

### D.2.1    Text Statements

One of the simplest BLASTED commands puts text on the screen **and allows user to** change text. The format is:

```
*|*      Text              | Optional input
```

The asterisk following the vertical line tells BLASTED that this is a **text statement** with optional user input. Here is an example from a BLAST input file.

```
*|*                               EIGHTEEN ZONE MULTI-STORY  STRUCTURE
*|*
*|*
*|*                     Date:|5 FEB 95
*|*               Filename:|MULTISTO.BIN
*|*
```

Here is what the user sees on the screen:

```
                        EIGHTEEN ZONE MULTI-STORY STRUCTURE


                  Date:   5 FEB 95
              Filename:   MULTISTO.BIN
```

The user can point and click on "5 FEB 95" or "MULTISTO.BIN" and type in new
text replacing the old. Note that the text is ignored by BLAST because the lines
containing it start with an asterisk. This BLASTED command is used primarily for
providing on-screen instructions to the user.

### D.2.2    File Reference Statement

Another BLASTED command is the File Reference statement. Its format is:

```
*|<     Text              |Filename|Display Field| Value Field|HelpNo
```

This command creates a scrollable list when the user clicks on the field.

The "<" tells BLASTED that this is a File Reference statement. "Text" is displayed
on the screen. "Filename" is the name of the file containing the scrollable list.

"Display Field" is the number of the column in the file containing the text that is to
be displayed.

"Value Field" is the number of the column containing the corresponding BLAST
input.

"HelpNo" is a number from 1 to 999 that refers to paragraphs of help text that are
displayed when the user hits the F1 key. See the section below entitled BLASTED
Help.

In many cases the Display Field and Value Field are the same. For example, in the
BLAST input file:

```
BEGIN FAN SYSTEM DESCRIPTION;
VARIABLE VOLUME
*|<SELECT A FAN SYSTEM            |fansys.dat|1|1|200
```

results in

```
SELECT A FAN SYSTEM              VARIABLE VOLUME
```

being displayed on the screen.  The file fansys.dat is:

```
18
DUAL DUCT
DUAL DUCT VARIABLE VOLUME
DUAL DUCT VARIABLE VOLUME
DX PACKAGED UNIT
FOUR PIPE FAN COIL
FOUR PIPE INDUCTION UNIT
HEAT PUMP PACKAGED UNIT
MULTIZONE
SINGLE ZONE DRAW THROUGH
SUBZONE REHEAT
TERMINAL REHEAT
THREE DECK MULTIZONE
TWO PIPE FAN COIL
TWO PIPE INDUCTION UNIT
UNIT HEATER
UNIT VENTILATOR
VARIABLE VOLUME
WATER LOOP HEAT PUMP
```

When the user clicks on the name "VARIABLE VOLUME" on the screen, a menu containing the eighteen allowable fan system types appears.  If the user selects another fan system type, then "VARIABLE VOLUME" on the line previous to the BLASTED command will be replaced with the new name.  Notice that the file containing the list has the number of rows in the file as its first element.

Here is another example:

```
RUN CONTROL:
  NEW ZONES,
  NEW AIR SYSTEMS,
  PLANT,
  REPORTS(ZONE LOADS),
```

```
      UNITS(IN=ENGLISH, OUT=ENGLISH)
,DESIGN SYSTEMS
*|<DESIGN SYSTEMS?|DESSYS.DAT|2|1|99
*
,DESIGN PLANT;
*|<DESIGN PLANT ? |DESPLT.DAT|2|1|99
```

The DESSYS.DAT file is:

```
2
 *#No Don't design systems
,DESIGN SYSTEMS#  Yes calculate air volume flow rates
```

and the DESPLT.DAT file is:

```
2
;#   No Don't design central plant
,DESIGN PLANT;#Yes size the central plant
```

On the screen, the user sees:

DESIGN SYSTEMS?   Yes calculate air volume flow rates
DESIGN PLANT ?    Yes size the central plant

In these instances the display field is column 2 and the value field is column 1. In the first instance, if the user chooses "No Don't design systems" after clicking on the text next to the "DESIGN SYSTEMS? " prompt, BLASTED will place an "*" on the previous line of the BLAST input file (a comment as far as BLAST is concerned). If the user chooses the other alternative, "Yes calculate air volume flow rates," then ",DESIGN SYSTEMS" will be placed on the previous line as is shown above. Similar results occur for the "DESIGN PLANT ?" prompt.

Notice that the columns of data are separated with the "#" symbol.

File Reference commands are used extensively in the BLAST input files, especially when selecting items from the BLAST libraries. A general discription of the files containing lists is given in Table D1.

**Table D.1. BLASTED files containing lists.**

| | |
|---|---|
| **boilers.dat** | A list of allowable central plant heating equipment. |
| **ceiling.dat** | A list of ceilings in the BLAST library. |
| **chillers.dat** | A list of allowable central plant chilling equipment. |
| **contrl.dat** | A list of room temperature control strategies in the BLAST library. |
| **coolstor.dat** | A list of central plant cold storage chillers. |
| **deckcon.dat** | A list of control options for fan system hot and cold decks. |
| **desday.dat** | A list of all the named design days in the BLAST library. |
| **desplt.dat** | A file for choosing the DESIGN PLANT run control option. |
| **dessys.dat** | A file for choosing the DESIGN SYSTEM run control option. |
| **esource.dat** | A list of energy sources (i.e., HOT WATER) for various fan system components (i.e., reheat coils, baseboard heaters, etc.). |
| **evapcool.dat** | A list of allowable fan system evaporative cooling options. |
| **exwalls.dat** | A list of all exterior walls in the BLAST library. |
| **fansys.dat** | A list of all the allowable name of fan systems. |
| **floors.dat** | A list of all the floors in the BLAST library. |
| **hotwater.dat** | A list of allowable central plant domestic water heaters. |
| **integer.dat** | A list of integers used in various places where BLAST requires an integer without a decimal point (i.e. when specifying the number of boilers or chillers). |
| **locat.dat** | A list of all the locations in the BLAST library. |
| **mater.dat** | A list of all the materials in the BLAST library. |
| **mixedair.dat** | A list of allowable fan system mixed air control strategies. |
| **preheat.dat** | A list of allowable locations for the preheat coil (including NONE). |
| **ptwalls.dat** | A list of all the partitions in the BLAST library. |
| **roofs.dat** | A list of all the roofs in the BLAST library. |
| **schedl.dat** | A list of all the schedules in the BLAST library. |
| **simtime.dat** | A file for selecting the simulation period (i.e., design days only or design days plus a one-year simulation). |
| **towers.dat** | A list of central plant heat rejection devices (i.e., COOLING TOWERS, EVAPORATIVE CONDENSER, etc.) |

### D.2.3    Constants/Equations Statements

Another type of BLASTED command, the Constants/Equations statement, is used
to manipulate numerical data.  Here is an example:

```
*|*Select the floor to floor height:
        HEIGHT=         10.0000
*|FLOOR TO FLOOR HEIGHT|ft|ft|0|1|0.0|1000.0|108
```

The statement allows the user to change a number following an equal sign on the
previous line.

Here is what is seen on the screen:

```
Select the floor to floor height:
FLOOR TO FLOOR HEIGHT  10.0   ft
```

The number 10.0 will be in a highlighted field and users can type in a new number.
The general format is:

```
*|Descriptive text|Primary Units|Secondary Units|Add|Mult|Min|Max&Format|HelpNo
```

The words "Descriptive text" are displayed on the screen.

The "Primary Units" field can be used to remind the those looking at the BLAST
input deck of the units of the variable.

The "Secondary Units" field contains text that is displayed to the right of the number
on the screen.

"Add" and "Mult" are used for units conversion when necessary.  The formula is:

```
Secondary Unit Value = (Primary Unit Value + Add) * Mult
```

The primary unit value is the number next to the equals sign in the BLAST input file. The secondary unit value is what BLASTED displays on the screen.

"Min" is the minimum value that can be entered in the number field.

"Max&Format" determines the maximum number that can be entered and the number of decimal places that will be displayed. For example, if the "Max" field contains 300.0 then the largest allowable value is 300 and the value will be displayed with one digit following the decimal point.

The same Constants/Equation statement can be used with numbers that are not preceeded by an equals sign provided the numbers are the only thing that appear on the line previous to the BLASTED command.

### D.2.4    Text Replacement Statements

Text replacement statements are used to replace text on the preceeding line. For example:

```
     BUILDING=
 "Multi story office"
*|ENTER BUILDING NAME   |Not Used|  |  |  |70|105
```

The general form is:

```
*|Descriptive Name |Not used|Display Units |  |  |  |MaxLen|HelpNo
```

The MaxLen field indicates the maximum number of characters
allowed for the text input.

## D.3  BLASTED Help

Users can uses the F1 key anytime BLASTED is running and context sensitive help text will appear on the screen. This is made possible by the existence of a help.hlp

file that is accessed by BLASTED whenever the F1 key is pressed. Help text can be added or changed by editing the help.txt file and then recompiling this file using the command:

```
helpcom help.txt
```

This command creates a new help.hlp file for BLASTED to use. When a user clicks on a particular field on the BLASTED screen and presses F1, BLASTED matches the number of the help text given at the end of the BLASTED command in the BLAST input file with the corresponding number given in the help.txt file. For example, the text below from the help.txt file defines what will be displayed if the user presses F1 and the help number in the BLASTED command is 98, 99, or 104.

```
.topic  designsytemandplant=98
You can specify the air volume flow rate for each zone and the capacity of the
central plant components or you can let BLAST automatically calculate the air
volume flow rates and select the capacity of the central plant.

topic simulationperiod=99
BLAST can simulate design days, a full year, or both.  The
choice that has been implemented here allows you to choose
design days only or design days followed by 365 days starting
January 1 and ending December 31.

The recommended approach is to first simulate design days and
inspect the output.  If you are satisfied with the design day
results then proceed to simulate both design days and a full year.

.topic Materials=104
The BLAST materials library is organized like Table 4 of Chapter
22 of the ASHRAE Handbook of Fundamentals.  In addition, most of the
materials with code numbers given in Table 11 of Chapter 26 are also
in the library.
```

To clarify how help works, consider that the following lines in a BLAST input file:

```
,DESIGN SYSTEMS
*|<DESIGN SYSTEMS?|DESSYS.DAT|2|1|98
```

causes the line:

```
DESIGN SYSTEMS?    Yes calculate air volume flow rates
```

to appear on the BLASTED screen.  The phrase:

```
Yes calculate air volume flow rates
```

appears in a field next to DESIGN SYSTEMS?  If the user clicks on that field it become highlighted.  If the user then presses F1, the following text appears in the help window that appears on the screen:

```
You can specify the air volume flow rate for each zone and the capacity of the
central plant components or you can let BLAST automatically calculate the air
volume flow rates and select the capacity of the central plant.
```

The above is the text associated with HelpNo 98.

The general form for each help file topic is:

```
.topic onewordname=HelpNo
```

Any text that appears between this statement and the next ".topic" statement will be displayed on the screen when appropriate.

The format of the text (i.e., line length) depends on the size of help window on the screen.  This window can be resized by the user.

While help text numbering is arbitrary, numbers below 100 tend to deal with lead input in BLAST, numbers between 100 and 200 deal with building description topics, number between 200 and 300 deal with fan system description topics and number 300 and above deal with central plant description topics.

## D.4 BLASTED Options

As readers can imagine, BLASTED commands can be embedded in BLAST input files to create as rich a user interface as the super user and other users desire. For example, the ability for users to define new material, schedules, control strategies, etc. could be added. The names of these items must then be added to the corresponding .dat files. As another example, wings and overhangs could be added to exterior wall. Input files with basements could also be added.

Increasing complexity has some disadvantages. It will slow BLASTED down. The user will also have to deal with more input fields and this will slow the data preparation process. Also, so far, the same .dat files have been used for all the BLAST template files. If .dat files are changed to accommodate changes to one template, then all the other templates need to be changed accordingly (so that being able to define a new material is in all the files, for example). Alternatively, custom .dat file can be used for each template, significantly increasing the number of such files.

The hoped mode of operation for BLASTED is that the super user in any organization can customized the template files for their mode of operation, not necessarily adding to the complexity of the files but letting users see inputs that need to be changed and hiding inputs that do not need to be changed. The super user may also want to create new templates for applications that are frequently part of the organization's work load.

# Appendix E:  TRNSYS Input Deck for Bell Avenue School

This appendix includes an example of a complete TRNSYS deck used to estimate the
beam and diffuse radiation components from the measured total radiation on a
horizontal surface.  The TRANSYS data are developed for inclusion into the overall
BLAST building model.  Various aspects of the deck must be changed for different
building locations and times of year, but the general format remains the same.

```
*   TRNSYS input deck; Sacramento Ihoriz data from Ed Hancock.
*   This deck takes measured radiation on a horizontal surface and gives
*   the beam and diffuse values needed for a BLAST weather file.
*   This file will generate the beam and diffuse radiation components from
*   0100 Saturday day 351 (Sat in 1994) and through 2400 Tuesday day 354
*   The original data includes 6 hours from Fri and 7 from the
*   following Wed.; these were omitted in this calculation.  The beam and
*   diffuse results from Saturday will be used to simulate Friday weather data

*   Assign file names to logical units
Assign SACRSUN.LST 6
*   data read into data reader from file SACRSUN.DAT
Assign SACRSUN.DAT 10
*   output from printer to file SACRSUN.OUT
Assign SACRSUN.OUT 11
*
*   Equations
*
Equations 10
*   simulation period
HSTART=1.0
HSTOP=96.0
TSTEP=1.0
*   parameters for solar radiation processor
DAY=351
LAT=38.5
SC=4871
SHIFT=-1.5
*   inputs to radiation processor
RHO=0.2
SLOPE=0.0
AZIMUTH=0.0
*
*   Simulation
*
```

```
Simulation HSTART HSTOP TSTEP
*
*   set output width
*
Width 72
*
*   Type 9, Data Reader
*
Unit 9 Type 9 Input Data Reader
Parameters 7
*   no interpolations, read in all three columns, no format
*   multiplying W/m^2 to get kJ/m^2-hr
1.0 TSTEP -1.0 3.6 0.0 10 0.0
*
*   Type 16, Solar Radiation Processor
*    .
Unit 16, Type 16 Solar Processor
Parameters 8
*   IE=0 (last parameter) don't treat simulation time as solar time
*   default is zero, so could just leave IE off
3.0 1.0 4.0 DAY LAT SC SHIFT 0
Inputs 6
9,1 9,19 9,20 RHO SLOPE AZIMUTH
0.0   0.0   0.0 RHO SLOPE AZIMUTH
*
*   Type 25, Printer
*
Unit 25 Type 25 Printer
Parameters 4
*   last parameter prints to unit 11, SACRSUN.OUT
TSTEP HSTART HSTOP 11
Inputs 3
16,7 16,8 9,1
IBEAM  IDIFF  IDATA
*
End
```

# Appendix F:  PERL Scripts for Model Calibration

This appendix includes the PERL scripts used during the model-calibration process described in Appendix A.

### change

```perl
#   change file - this file modifies selected parameters in the stem.bin file,
#   runs BLAST, determines the rms error and R metric between the BLAST
#   annual.rwd and meas.dat files, and collects the values for one parameter
#   and all percent changes in a single file.
#
#   required input parameters to this perl script include the start and stop
#   fractional values for the varying parameters, the step size (ie 10%) and
#   the material (WALLINS1) and parameter (R) to be varied.
#
#   clean up directory in case any of these files already exist
#
system("IF EXIST rmse.out DEL rmse.out");
system("IF EXIST answer.out DEL answer.out");
#
#   Variable definitions
#
open (HEADINGS,">headings");
open (FRACTION,">frac.out");
($binfile,$blstbatch,$measdata,$rmsestart,$rmsehours,$start,$stop,$step,@ARGV)
= @ARGV;
#
$j=1;
while (@ARGV)   {
  $def_name=shift(@ARGV);
  push(@def_name,$def_name);
  $param_name{$j} = shift(@ARGV);
  $j += 1;
#  print HEADINGS "\"$def_name\" \"$param_name{$def_name}\"\n";
}
#
@headings = ('"fraction"');
@fraction = ();
$new_name='"'.$def_name.'-'.$param_name{1}.'"';
push(@headings,$new_name);
for ($fraction=$start; $fraction<=$stop; $fraction =
 sprintf("%.6g",$fraction+=$step)) {
```

```
  $percent = sprintf("%.1d",$fraction*100);
#  print "percent = $percent\n";
  $percent = '"p'.$percent.'"';
  system("copy $binfile stemax.bin");
  print "fraction = $fraction\n";
  $newfrac = $fraction."\n";
  push(@fraction,$newfrac);
#
#  Modify the .bin file
#
  $j=1;
  foreach $def_name (@def_name) {
    print "foreach loop: $def_name $param_name{$j}\n";
    system("perl jmodify $def_name $param_name{$j} $fraction stemax.bin");
    if (-e 'temp') {
      die "ERR *****\n  CHANGE:  JMODIFY died - no changes made.\n";
    }
    $j += 1;
  }
#
#  Run BLAST
#
  system("$blstbatch");
#
#  determine the rms error and R metric
#     the inputs are the measured data file, the comparison period start time
#     and the number of comparison hours
  system("perl rmse $measdata $rmsestart $rmsehours");
}                          #outputs in rmse.out and r.out
#
#  Collect the rms error results
#
print FRACTION @fraction;
close(FRACTION);
system("perl paste frac.out rmse.out");
      #output is paste.out
system("del frac.out");
system("del rmse.out");
#
#  Collect the R metric results
#
system("move paste.out more.out");
system("perl paste more.out r.out");
      #output is paste.out
system("del more.out");
system("del r.out");
push(@headings,"\"R metric\"");
#
#  put headings on each changed column
#
print HEADINGS join("\t",@headings),"\n";
#headings are the varying parameters
close(HEADINGS);
system("copy headings+paste.out answer.out");
system("del headings");
system("del paste.out");
```

```
system("del stemax.*");
#answer.out:RMS error for all fractions of one parameter
#
#  Gather all the rms data in one file for each run
#
unless (-e 'rmseall.out') {
  system("copy answer.out rmseall.out");
#answer.out from above
} else {
  system("perl join rmseall.out answer.out");
  system("del rmseall.out");
  system("copy join.out rmseall.out");
  system("del join.out");
}
system("del answer.out");
#
#  the end


           *********************************************
```

## simdat

```
#  simdat - this file modifies selected parameters in the stem.bin file,
#  runs BLAST, determines the rms error between the BLAST annual.rwd and
#  meas.dat files, and collects the percent change, rms error and simulated
#  data in a single column file with the parameter header.
#
#  required input parameters to this perl script include the name of the .bin
file
#  to be changed, the name of the batch file (needed to specify the right
weather
#  file), the correct measured data file, comparison start time and duration
(hrs),
#  the start and stop range over which to vary the selected parameter, the
step size
#  (eg 0.1 for 10%) and the. material (eg WALLINS1) and parameter (eg R) to be
varied.
#
#  clean up directory in case any of these files already exist
#
system("IF EXIST rmse.out DEL rmse.out");
system("IF EXIST answer.out DEL answer.out");
#
#  Variable definitions
#
open (HEADINGS,">headings");
($binfile,$blstbatch,$measdata,$rmsestart,$rmsehours,$start,$stop,$step,@ARGV)
= @ARGV;
#
$j=1;
while (@ARGV)   {
  $def_name=shift(@ARGV);
  push(@def_name,$def_name);
  $param_name{$j} = shift(@ARGV);
```

```perl
  $j += 1;
}
#
$new_name1='"'.$def_name.'"';
$new_name2='"'.$param_name{1}.'"';
push(@headings,$new_name1,$new_name2);
for ($fraction=$start; $fraction<=$stop; $fraction =
 sprintf("%.6g",$fraction+=$step)) {
  $percent = sprintf("%.1d",$fraction*100);
  $percent = '"'.$percent.'%"';
  system("copy $binfile stemax.bin");
  print "fraction = $fraction\n";
  $newfrac = $fraction."\n";
  push(@headings,$percent);
#
#  Modify the .bin file
#
  $j=1;
  foreach $def_name (@def_name) {
    print "foreach loop: $def_name $param_name{$j}\n";
    system("perl jmodify $def_name $param_name{$j} $fraction stemax.bin");
    if (-e 'temp') {
      die "ERR *****\n  CHANGE:  JMODIFY died - no changes made.\n";
    }
    $j += 1;
  }
#
#  Run BLAST
#
  system("$blstbatch");
#
#  determine the rms error and R metric
#
#  the inputs are the measured data file, the comparison period start time
#  and the number of comparison hours
  system("perl rmse $measdata $rmsestart $rmsehours");
}                              #outputs in rmse.out and r.out
#
#  Collect the rms error and R metric results
#
open(RMSE,"rmse.out")|| die "SIMDAT: could not open rmse.out for reading.\n";
open(R,"r.out")|| die "SIMDAT: could not open r.out for reading.\n";
chop($rmse = <RMSE>) || die "SIMDAT: no rms error in rmse.out.\n";
chop($r = <R>) || die "SIMDAT: no R metric in r.out.\n";
push(@headings,"\"RMS error\"",$rmse,"\"R metric\"",$r,"\"******\"");
print HEADINGS join("\n",@headings),"\n";
#delimit headings with newline
close(HEADINGS);
close(RMSE);
close(R);
#
#  Collect the simulated data from annual.rwd
#
open(FILEIN,"annual.rwd") || die "SIMDAT:  Could not open BLAST output for
reading.\n";
```

```
open(FILEOUT,">energy.out") || die "SIMDAT:  Could not open energy.out for
writing.\n";
for ($i=0; $i<31; $i++) {
#gets rid of 31 lines including $i<#
  $a=<FILEIN> || die "SIMDAT:  the BLAST output file (annual.rwd) is empty\n";
}
while(<FILEIN>) { #read a line from annual.rwd to $_
  print FILEOUT $_;       #print that line to energy.out
}
close(FILEIN);
close(FILEOUT);
#
#  put headings on each changed column
#
system("copy headings+energy.out answer.out");
system("del headings");
system("del energy.out");
system("del stemax.*");
#
#  clean up
#
system("del rmse.out");
system("del r.out");
#
#  the end


                **************************************************
```

## jmodify

```
#!/usr/local/bin/perl
#
#   This perl code looks for line containing the string $find_string
#     in the file $input and replaces these lines with the assignment
#     line, $find_string = $new_value.
#
($line_name,$variable_name,$fraction,$input) = ();
($line_name,$variable_name,$fraction,$input) = @ARGV;
print "$line_name, $variable_name, $fraction, $input\n";
open (INPUT,"$input") || die "Could not open $input for reading!\n";
open (TEMP,">temp") || die "Could not open temp for writing!\n";
$flag=1;
while (<INPUT>) {                          #read the .bin file line by line
  if (/(.*\b$line_name\b)/i) {             #if line contains $line_name exactly,
then
    undef($flag);
    if ($1 =~ /\*\*/) {                    #if match was part of a comment
statement
      print TEMP $_;                         #just echo line to temp file
    } else {                              #else,
      print "Found a match;\n";
      until (/;/) {                        #until a ";" is found
        /($variable_name\s*=\s*)([\+\-]*\d*\.*\d*)/i;  #find desired variable
assignment
```

```perl
        $new_value = sprintf("%.14g",$2*$fraction);      #modify the assigned
value by $fraction
#        print "new_value = $new_value\n";
        s/($variable_name\s*=\s*)([\+\-]*\d*\.*\d*)/$1$new_value/i;   #modify
line
        print TEMP $_;                          #write the line to temp file,
and
        print $_;
        $_ = <INPUT>;                           #read the next line
      }                                         #don't forget the last line
        /($variable_name\s*=\s*)([\+\-]*\d*\.*\d*)/i;   #find desired variable
assignment
        $new_value = sprintf("%.14g",$2*$fraction);      #modify the assigned
value by $fraction
#        print "new_value = $new_value\n";
        s/($variable_name\s*=\s*)([\+\-]*\d*\.*\d*)/$1$new_value/i;   #modify
line
        print TEMP $_;                          #write the line to temp file
        print $_;
    }
  } else {                             #else,
    print TEMP $_;                     #just echo line to temp output
  }
}
if ($flag) {
  die "ERR *****\n  JMODIFY:  No changes made to .bin file.  Check your input
line.\n";
}
close (INPUT);
close (TEMP);
system ("copy temp stemax.bin");
#rename temp file to stemax.bin
system ("del temp");


        *************************************************


rmse


#!/usr/local/bin/perl
#
#  This code finds the rms Error and R metric of measured data compared to
BLAST output
#
($measdata,$start,$hours) = @ARGV;
#assign command line arguments
#
#  Open files for input.
#
open(FILE0,"$measdata") || die "RMSE:  Could not open $file0 for reading\n";
open(FILE1,"annual.rwd") || die "RMSE:  Could not open $file1 for reading\n";
#
#  skip over the first 31 lines of the BLAST annual.rwd file (assuming BLAST
runs
#  one full day before collecting the data) and to $start hour of test period
#
```

```
$start=$start-1;
for ($i=0; $i<($start); $i++) {
        #gets rid of lines including $i<#
  <FILE0> || die "RMSE:  the measured data file (meas.dat) is empty\n";
}
for ($i=0; $i<(31+$start); $i++) {
    #gets rid of lines including $i<#
  $a=<FILE1> || die "RMSE:  the BLAST output file (annual.rwd) is empty\n";
}
#
#  Open the output file.
#
$output = "rmse.out";
open(OUTPUT,">>$output") || die "Could not open $output for output\n";
#appends to a file
open(ROUT,">>r.out") || die "Could not open r.out for output\n";
#appends to a file
#
#  determine rms error and R metric, reading both files line by line
#
$n=0;
while ($n<$hours) {
  chop($_=<FILE0>);
#get line from measured data file
#   s/[\n\r]//g;
#remove new line and/or line feed
  s/^\s+//;
#delete leading blanks
  @meas=split;
#split at white spaces into an array of values
  chop($_ = <FILE1>);
  s/^\s+//;
#delete leading blanks
  @blast=split;
  $r+=($meas[1] - $blast[0]);                                            #sum
the differences
  $rsq+=($meas[1] - $blast[0])**2;
#sum the square of the difference
#   print "$meas[1], $blast[0], $rsq\n";
  $n+=1;
}
$rmse=sqrt($rsq/$hours);
$rmse=sprintf("%8.3f",$rmse);
$r=sprintf("%8.2f",$r);
print "RMS Error is $rmse, and R is $r\n";
print OUTPUT "$rmse\n";
print ROUT "$r\n";
#
#  The end
#
close(FILE0);
close(FILE1);
close(OUTPUT);
close(ROUT);
```

```
*********************************************
```

## paste

```
#!/usr/local/bin/perl
#
#  This perl code PASTEs (to the right) the contents of several files.
#
($file0,@file_list) = @ARGV;                    #assign command line arguments
$file0 || die "PASTE:  You must specify at least two files on the command
line\n";
$file_list[0] || die "PASTE:  You must specify at least two files on the
command line\n";
#
#  Open first file for input.
#
open(FILE0,"$file0") || die "PASTE:  Could not open $file0 for reading!\n";
#
#  Open the remaining files in the file list for input.
#
$n = 0;
foreach $file (@file_list) {
  $n += 1;
  $handle = "FILE"."$n";
  @handles = (@handles,$handle);
  open("$handle","$file") || die "PASTE:  Could not open $file for read-
ing!\n";
}
#
#  Open the output file.
#
$output = "paste.out";
open(OUTPUT,">$output") || die "Could not open $output for output!\n";
#
#  Read lines from each file and paste together until no more lines.
#
while (<FILE0>) {
  chop;
  s/[\n\r]//g;                         #remove new line and/or line feed
  s/^\s+//;                            #delete leading blanks
  (@values) = split;
  foreach $handle (@handles) {
    chop($_ = <$handle>) || die "PASTE:  $handle file is empty\n";
    s/[\n\r]//g;                       #remove new line and/or line feed
    s/^\s+//;                          #delete leading blanks
    (@new_values) = split;
    @values = (@values,@new_values);
  }
  print OUTPUT join("\t",@values),"\n";
}
#
#  That's all there is to it.
#
close(FILE0);
close(OUTPUT);
```

**************************************************

## join

```
#!/usr/local/bin/perl
#
#  This perl code PASTEs (to the right) the contents of several files.
#
($file0,$file1) = @ARGV;
      #assign command line arguments
$file0 || die "PASTE:  You must specify at least two files on the command
line\n";
$file1 || die "PASTE:  You must specify at least two files on the command
line\n";
#
#  Open files for input.
#
open(FILE0,"$file0") || die "PASTE:  Could not open $file0 for reading!\n";
open(FILE1,"$file1") || die "PASTE:  Could not open $file1 for reading!\n";
#
#  Open the output file.
#
$output = "join.out";
open(OUTPUT,">$output") || die "Could not open $output for output!\n";
#
#  Read lines from each file and paste together until no more lines.
#
@file0=<FILE0>;
#print "@file0";
@file1=<FILE1>;
#print "@file1";
$first=1;
if ($#file0>$#file1) {$max=$#file0;} else {$max=$#file1;}  #finding longest
file
print "The size of file0 is $#file0\n";
print "The size of file1 is $#file1\n";
print "the max is $max\n";
for ($i=0; $i<=$max; $i++) {
      #run loop through the longest file
  chop($file0[$i]);
  chop($file1[$i]);
  @values0 = split(/\t/,$file0[$i]);
      #splits the line on a single tab
  @values1 = split(/\t/,$file1[$i]);
  if ($first) {
    $size0 = $#values0;
      #first time thru, set line length=size0
    $size1 = $#values1;
    print "size0 = $size0\n";
    print "size1 = $size1\n";
    undef($first);
  } else {
    $#values0 = $size0;
      #line length is always the same value
    $#values1 = $size1;
    for ($j=0; $j<=$size0; $j++) {
      unless ($values0[$j]) {$values0[$j]=' ';}
#replace single white space with " "
```

```
#      print "$values0[$j]\n";
     }
  }
  @values = (@values0,@values1);
  print OUTPUT join("\t",@values),"\n";
  undef(@values0);
  undef(@values1);
}
#
# the end
#
close(FILE0);
close(FILE1);
close(OUTPUT);
```

# Appendix G: Description of Test Buildings

The STEM protocol was used to collect data from four commercial buildings during this program. Three of the buildings were single-story structures of varying size with floor areas from 4,320 to 12,500 sq ft. The fourth and largest was a nine-story office building with about 10,000 sq ft per floor.

## G.1  Building 7108, Fort Riley, Kansas

The first building evaluated, Building 7108, is the headquarters for an Air Defense Artillery Battalion at Fort Riley, Kansas. It is located at about 39.15 degrees north latitude, 96.7 degrees west longitude, and 1,300 ft above sea level.

Building 7108 is a single-story, approximately rectangular structure with the interior space composed of offices, classrooms and a cryptography facility. The inside floor area covers about 12,500 sq ft. Figure G.1 shows the building floor plan. The north face of the building is oriented approximately 30 degrees to the east of north.

The floor of the building is a reinforced concrete slab-on-grade primarily covered with tile. The exterior wall consists of 6 in. thick bricks on the exterior, 6 in. to 12 in. thick concrete blocks on the interior, and 2 in. of rigid insulation in between. The interior wall finish is primarily a light color of paint coating the interior concrete blocks. The roof has a metal exterior surface, a wood decking, and 3 in. of rigid insulation. Most of the interior ceiling consists of acoustic tile panels suspended 9 ft above floor level. A large plenum space located between the tile ceiling and the roof serves as a return air passage for the HVAC system.

The building has about 450 sq ft of windows (3.6 percent of the floor area), approximately equally divided between the west- and east-facing walls. The north- and south-facing walls have no windows. The windows have standard, double panes with metal frames and are operable. All windows are set back into the walls at least 6 to 8 in., resulting in substantial exterior shading. Each window has Venetian blinds as well as drapery material, which, from general observation, cover about 70 percent of the total window area.
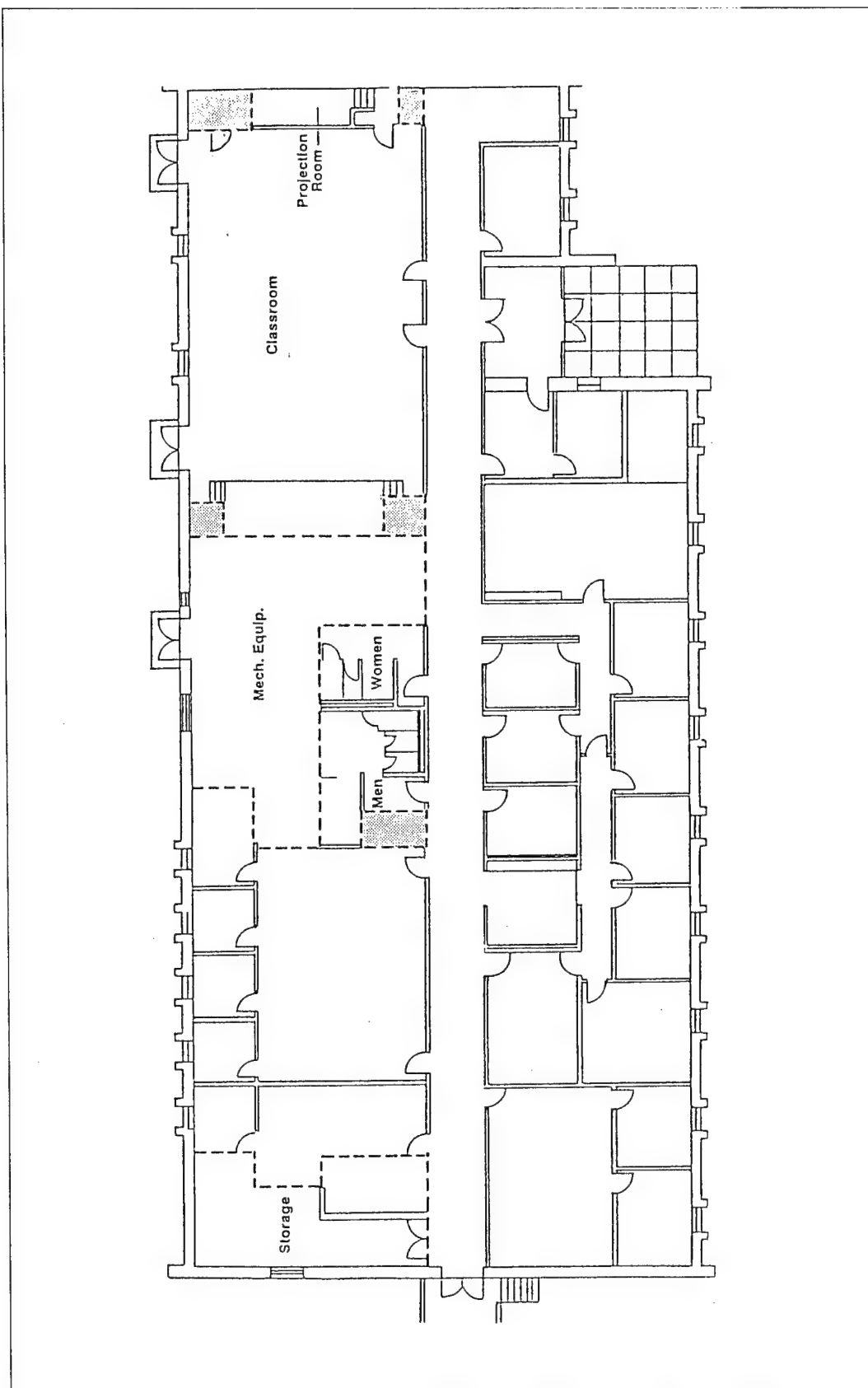
Classroom

Projection
Room

Mech. Equip.

Women

Men

Storage

**Figure G.1.  Building 7108 floor plan.**

The heating, cooling and ventilation requirements of the building are supplied by one multizone, constant-volume, air handling system and three unit heaters. The multizone system, located in the mechanical room, serves the majority of the building, while the unit heaters serve the mechanical room, storage room and entrance foyer. Hot and cold water to the system are supplied by a boiler and chiller located in a neighboring building about 200 ft to the north of Building 7108.
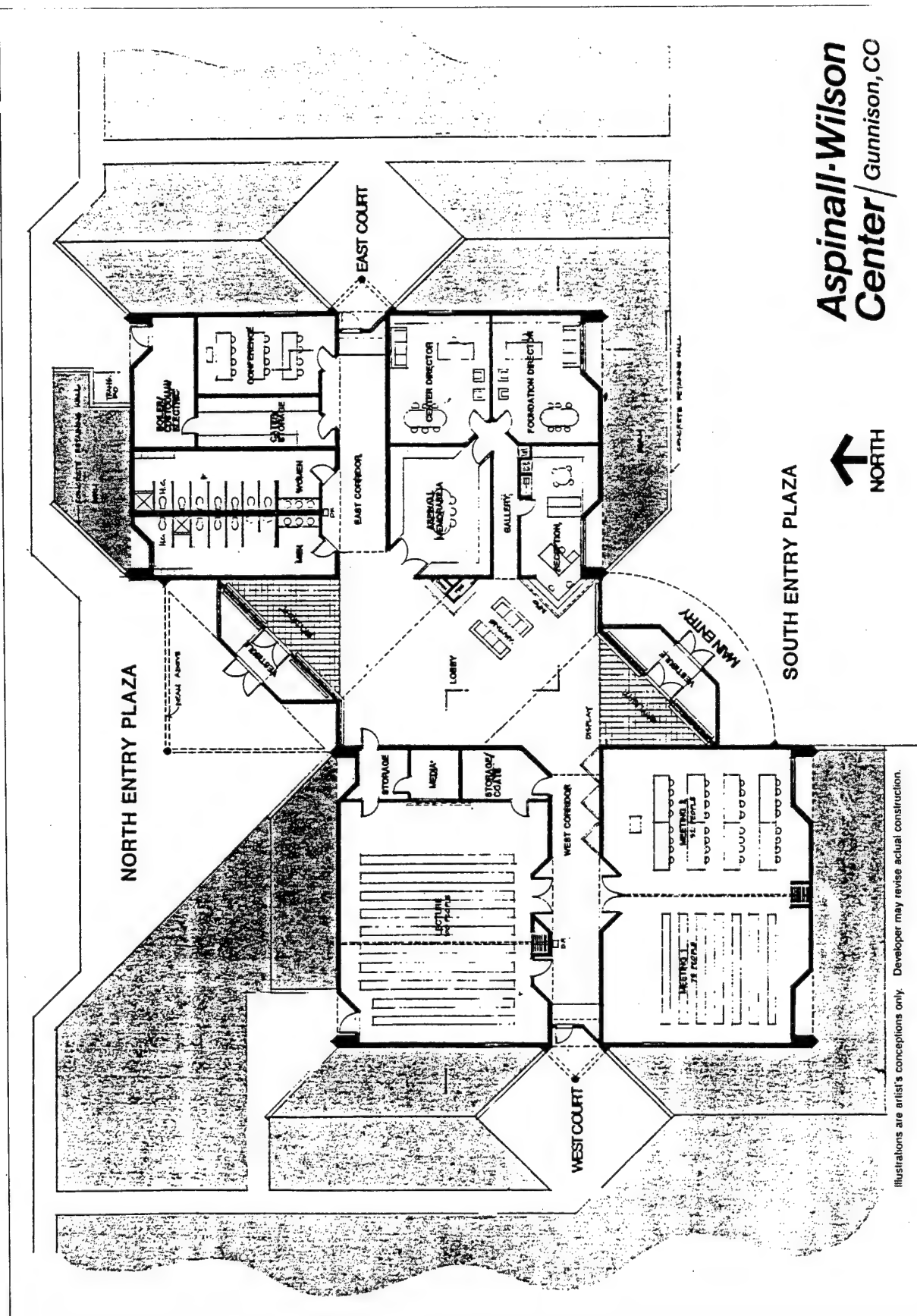
In general, this building has a straightforward design and construction which provided a fairly simple building model. However, because this was the first building to undergo the STEM testing protocol for commercial buildings, the data analysis and interpretation provided a challenge.

## G.2 Aspinall-Wilson Conference Center, Gunnison, Colorado

The Aspinall-Wilson Center, a relatively new building on the campus of Western State College, is located in Gunnison, Colorado at about 38.35 degrees north latitude, 106.5 degrees west longitude and at about 7,500 ft above sea level.

The conference center is a single-story structure with about 9,600 sq ft of floor space. The floor plan is shown in Figure G.2. The north side is oriented directly north. The building houses two lecture/meeting rooms, a good-sized lobby and reception area, several offices and a small commercial-like catering/storage area for food preparation and storage. An unconditioned mechanical room sits above the lobby. The building construction offers abundant daylighting from glazings that cover the entire south-facing roof of both the east and west corridors and from the north and south vestibules, which consist entirely of insulated glazings. A red brick interior surface provides thermal mass for absorbing and storing any heat entering the space through the glazing.

The floor of the building is concrete slab-on-grade covered primarily with commercial carpeting. The exterior walls, except lobby and vestibule glazings, are bermed to about 3 ft above the interior floor surface. The bermed-portion wall layers consist of 1 in. rigid insulation (exterior layer), 10 in. heavyweight concrete and 5/8 in. gypsum board (interior layer). The upper portion consists of 6-in. thick red brick (exterior layer), 3/4 in. plywood, 6-in. layer of R-19 insulation, and 5/8 in. gypsum board (interior layer). The interior surfaces in the vestibule, lobby and on the north sides of both corridors are red brick; the remaining interior surfaces are gypsum board painted a light color. The roof over the corridors is gabled, sloping 45 degrees to the north and south, with glazing on the south side and metal roofing, wood decking, R-19 insulation and 5/8 in. gypsum board on the north. The ceiling between

**Aspinall-Wilson Center**/Gunnison,CO

NORTH ENTRY PLAZA

EAST COURT

SOUTH ENTRY PLAZA

WEST COURT

NORTH

Illustrations are artist's conceptions only.    Developer may revise actual construction.

**Figure G.2.  Aspinall-Wilson Conference Center floor plan.**

the lobby and mechanical room is a 3 in. lightweight concrete layer with 5/8 in. gypsum board suspended below it. The roof over the lobby is flat with ballast roofing, wood decking, R-38 insulation and 5/8 in. gypsum board situated about 2 ft below the insulation layer. The remaining roofs have a metal exterior, wood decking, R-38 insulation and 5/8 in. gypsum board about 4 ft below the roof. The large plenum space between the ceiling and the roof serves as a return air passage for the HVAC system.

The building has about 1,680 sq ft of windows (16.6 percent of the floor area) which face primarily to the north and south, the majority of which make up the vestibule wall surfaces and the south-facing roofs of both corridors. The east- and west-facing glazings consist of double glass doors at the end of each corridor and portions of each vestibule. The windows are standard double pane with metal frames and are not operable. The office and meeting/lecture room windows are recessed about 2 in. into the walls, which is negligible compared to the 3 ft overhangs and building wings shading these windows. On the interior, each office and meeting room window has Venetian blinds, but no interior shading was observed.

The heating, cooling and ventilation requirements of the building are supplied by two variable air volume (VAV) air handling systems and three unit heaters. One VAV system serves the meeting and lecture rooms on the west side of the building; the second system serves the lobby and the offices and utility areas on the east side of the building. Both corridors and the mechanical room are all served by unit heaters. Hot water to the system is supplied by a simple fuel boiler located in the utility area of the building and cold water by direct evaporative cooling.

Various issues provided a challenge in developing an accurate simulation model of this building. The most difficult aspect was accurately modeling the orientation of the numerous windows and the interior surfaces receiving the incoming radiation. Many windows were tilted at angles difficult to model and had unusual shapes.

## G.3 Director Building, Portland, Oregon

The Director building is a renovated historical building located in downtown Portland, Oregon at about 45.6 degrees north latitude, 122.6 degrees west longitude and at about sea level.

The renovation in 1987 added a two-story penthouse and rooftop terrace to the original seven-story structure, and converted the lower underground level into a parking garage. The first two floors (ground floor and mezzanine) of the building are

primarily retail space (about 15,600 sq ft), with office space occupying the remaining upper floors of the building. The building has about 92,000 gross sq ft, of which 74,564 are conditioned. A generic floor plan for each floor is shown in Figure G.3.

The walls are constructed of heavy timbers and 16 in. to 20 in. thick brick with a 7/8 in. plaster finish. This basic wall structure has been furred out and R-7 batt insulation installed on all perimeter walls and finished with 5/8 in. gypsum board. The main building roof is wood frame construction with built-up roofing material, 3/4 in. plywood and R-30 insulation. The penthouse walls are constructed with filled concrete masonry units. The north and west penthouse walls are insulated with 1 in. polystyrene and the south and east walls with R-11 batt insulation. The
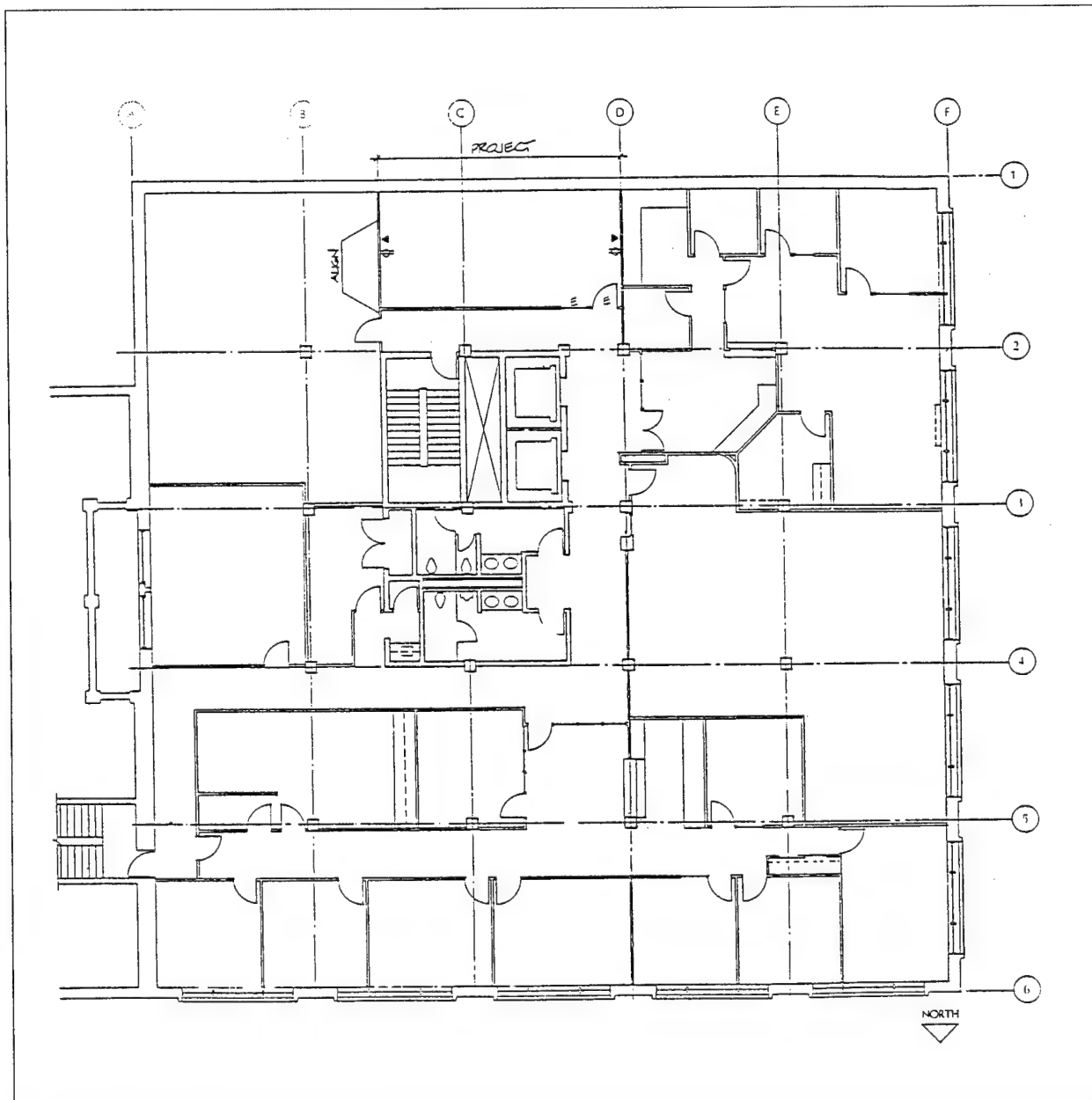


**Figure G.3. Director Building floor plan.**

penthouse roof consists of built-up roofing with R-20 rigid insulation. Portions of the south and east walls are shared by the neighboring buildings, but apparently have the same insulation and wall construction as the rest of the building.

The first and second floors consist of retail stores, a conference room, the lobby, a storage area, and bathrooms. The third floor tenant is an engineering firm, the fourth and fifth floors contain small office suites, only partially occupied, the sixth floor is divided between an advertising agency and government offices. The advertising agency also occupies the seventh floor and eighth and ninth floor penthouse. A 400 sq ft atrium rises three stories on the west side of the seventh, eighth and ninth floors.

The original single-pane operable windows in the office spaces were not replaced during the renovation. The windows in the retail space and penthouse and on the south and east side of the building are double pane. Two-inch wide horizontal reflective blinds, installed on the third through ninth floor windows, allow effective shading for the perimeter areas.

A mixture of console, horizontal, and vertical type unitary water source heat pumps are located in the tenant spaces. There are 2 to 23 heat pumps per floor, with a total of 93 in the entire building. A 30-ton, air-to-water heat pump located in the parking garage provides heating for the loop. An auxiliary, gas-fired boiler, located in the penthouse mechanical room, acts as a back-up when the heat pump fails to maintain the required loop temperature. A cooling tower, also in the penthouse mechanical room, supplies cooling to the loop.

Various aspects of this building, including the overall size, the significant mass in the form of the heavy timbers and thick brick walls, the occupancy distribution, and the 93 individual heat pumps serving the whole building, provided a modeling challenge. In addition, prior to this building, only single-story structures have been analyzed using the STEM protocol.

## G.4  Bell Avenue School, Sacramento, California

The Bell Avenue School is a relatively simple structure compared to the other test buildings. It is located at about 38.5 north latitude and 121.5 west longitude at about 30 ft above sea level.

The building selected for testing was one wing of the Bell Avenue Elementary School, which is a rectangular, single-story structure consisting of four adjoining classrooms.

The school was built in about 1960 and is typical of many similar schools of similar vintage in California. Each classroom has approximately 1000 sq ft of floor space. The long axis of the wing is oriented due east-west. Figure G.4 shows a basic floor plan of the building.

Building plans were not available for the structure, so various parameters were estimated based on the knowledge and experience of those measuring the building. The floor appears to be a concrete slab covered with linoleum tile. The exterior walls appear to consist of hollow, uninsulated cinder blocks with a stucco exterior and gypsum board interior finish. No insulation was noted in the wall construction, but the north wall has built-in cabinets about 12 in. deep which act as an insulating layer. The interior wall is finished primarily with a light-colored paint. The roof appears to be constructed from 2 x 12 lumber, probably 16 in. on-center with fiberglass insulation in the cavities between joists.

The building has about 820 sq ft of windows (19 percent of the floor area), two thirds of which are on the north-facing wall and one third on the south. A 20 in. overhang sets at the top of each row of windows, with the windows on the north more than twice the height of those on the south wall. A 9 ft overhang about 8 ft above the floor level extends from the east, west and south sides of the building. This overhang primarily shades the building walls, because the east- and west-facing walls have no windows, and the south has only one window on a door below this level. The windows have standard, double panes with metal frames. Less than one-third of the windows on the north side are operable, and the rest are not. No interior window shading was noted.

Each of the four classrooms is heated and cooled by its own residential-type furnace and air conditioning unit. A thermostat is located in each room and is controlled by the occupants during the day. An energy management system turns the system off after occupied hours.
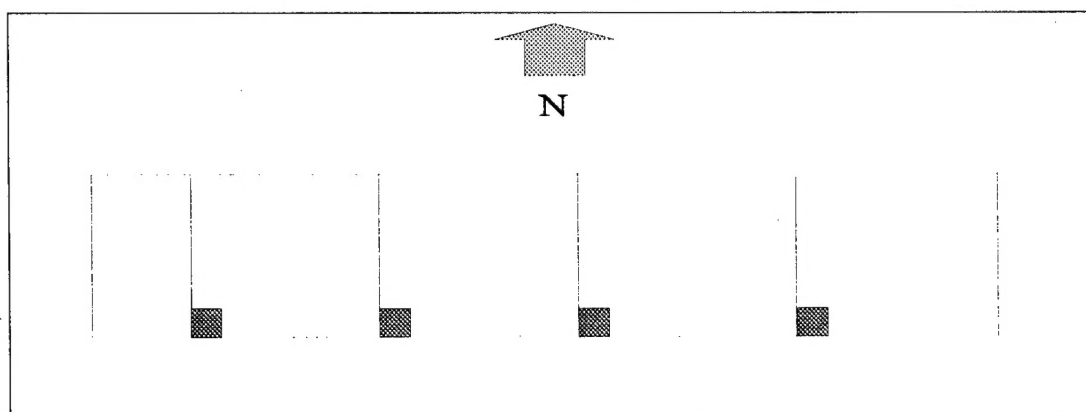


**Figure G.4. Bell Avenue School floor plan.**

This building, like the one in Fort Riley, is a simple structure that provides a straightforward approach for modeling. The primary difficulty was not having building plans to use for developing a more accurate base model. However, because the model parameters are being varied in the energy matching process, this was not difficult to overcome.

## USACERL DISTRIBUTION

Chief of Engineers
    ATTN: CEHEC-IM-LH (2)
    ATTN: CEHEC-IM-LP (2)
    ATTN: CECC-R
    ATTN: CECW-EE
    ATTN: CEMP-ET
    ATTN: CERD-C
    ATTN: CERD-L

CECPW 22310-3862
    ATTN: CECPW-E
    ATTN: CECPW-FT
    ATTN: CECPW-ZC

US Army Engr District
    ATTN: Library (40)

CEWES 39180
    ATTN: Library

CECRL 03755
    ATTN: Library

Engr Societies Library
    ATTN: Acquisitions 10017

US Military Academy 10996
    ATTN: MAEN-A
    ATTN: Facilities Engineer
    ATTN: Geography & Envr Engrg

Naval Facilities Engr Command
    ATTN: Naval Facilities Engr Service Center 93043-4328

Tyndall AFB 32403
    ATTN: HQAFCESA/CES
    ATTN: Engrg & Srvc Lab

US Gov't Printing Office 20401
    ATTN: Rec Sec/Deposit Sec (2)

Nat'l Institute of Standards & Tech
    ATTN: Library 20899

Defense Tech Info Center 22060-6218
    ATTN: DTIC-O (2)

                        66
                       7/96